U.S. DEPARTMENT OF THE NAVY
J.H. CHAFEE, Secretary

Naval Weather Service Command
E.T. HARDING, Captain, USN, Commander

U.S. DEPARTMENT OF COMMERCE
M.H. STANS, Secretary

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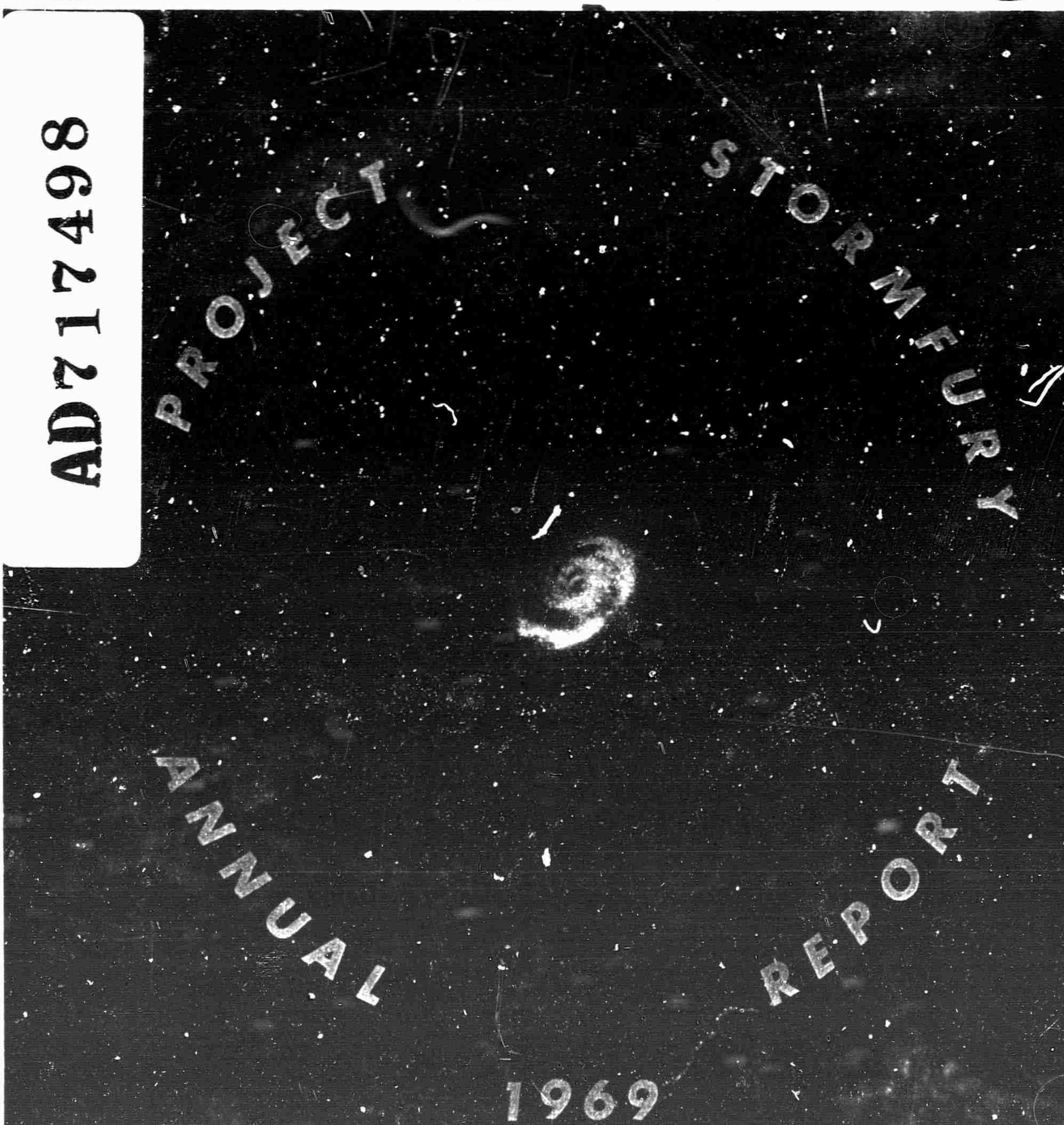

MIAMI, FLORIDA
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16. Abstracts

Project STORMFURY is a joint ESSA-Navy program of scientific experiments designed to explore the structure and dynamics of tropical storms and hurricanes and their potential for modification. It was established in 1962 with the principal objective of testing a physical model of the hurricane's energy exchange by strategic seeding with silver iodide crystals. These crystals have been dispensed by Navy aircraft using Navy-developed special pyrotechnic devices. The hypothesis calls for reducing the maximum intensity of a storm or hurricane by a measurable amount. Navy and ESSA scientists and aircraft, supplemented by those of the U.S. Air Force, have cooperated in STORMFURY Experimental operations since 1962 when the Project began. Until 1969, one mature hurricane (Beulah, 1963) and two series of tropical cumulus clouds (August 1963 and July-August 1965) had been experimentally seeded in the western Atlantic and Caribbean Sea.

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PROJECT STORMFURY ANNUAL REPORT 1969

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The cover is an enhanced photograph of the ATS III Satellite view taken of Hurricane Debbie, 201600Z August 1969.

We extend our thanks to the staff members of the National Aeronautics and Space Administration for the courtesies given to Project Stormfury, and to Dr. T. Fujita of the University of Chicago for his invaluable technical assistance.

Project STORMFURY was established by an interdepartmental agreement between the Department of Commerce and the Department of the Navy, signed July 30, 1962. Additional support has been provided by the National Science Foundation under Grant NSF-G-17993.

This report is the eighth of a series of annual reports to be prepared by the Office of the Director in accordance with the Project STORMFURY interdepartmental agreement.

Additional copies of this report may be obtained from:

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PROJECT STORMFURY ANNUAL REPORT - 1969

INTRODUCTION

The 1969 hurricane season was a highly productive one for Project STORMFURY, an interdepartmental program of the Department of Defense (Navy) and Department of Commerce, Environmental Science Services Administration (ESSA), with U.S. Air Force participation. STORMFURY forces operated during the dry run held at NAS, Jacksonville, Florida, 28-31 July; during the seeding of Hurricane Debbie, 18-and 20 August and during cloudline experiments conducted 9-19 September from the Naval Station, Roosevelt Roads, Puerto Rico.

Figure 1 shows the tropical cyclone tracks for 1969 near the STORMFURY areas. Of the storms, two were eligible for seeding under current criteria. Of these two, Debbie was seeded while Inga was not. Inga was technically eligible when near Bermuda, but was not seeded because she had poorly formed eyewall clouds, was weak, moved in an unusual manner, and in general was not desirable for experimentation.

The multiple eyewall seeding experiments conducted in Hurricane Debbie were very impressive. The intensity of the storm decreased on both seeding days. On 18 August, the maxi-maximum wind velocity decreased 31%, and on the 20th it decreased 15%. Whether this can be attributed to the seeding remains unproven because natural variations of this magnitude do occur in hurricanes. Data collected, however, strongly suggest that the experiments were successful. (See app. B for amplification.)

Figure 2 shows the track of Hurricane Debbie and the periods during which seeding was conducted. It also shows the operating area for the cloudline experiments.

An extensive amount of data was collected. Work on reducing and analyzing these data is continuing into 1970 and may extend into future years. New methods and techniques for expediting their processing are evolving and results will be available more quickly after future experiments. Considerable progress has been achieved in the development of numerical-dynamical modelling of hurricanes. Aspects of this will be further discussed in the "Research Activities" section of this report and in appendix C.

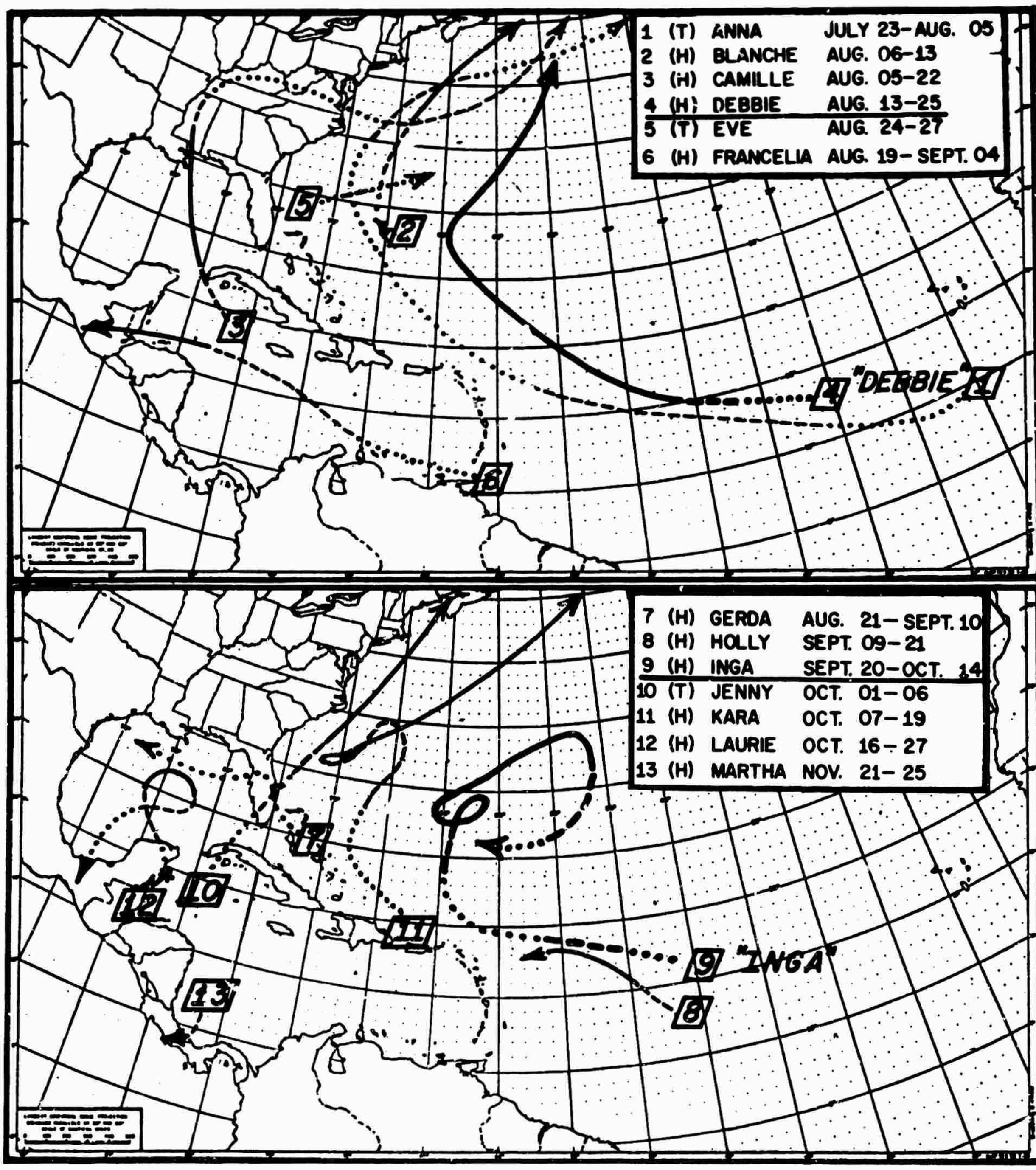

Figure 1. Tropical cyclone tracks.

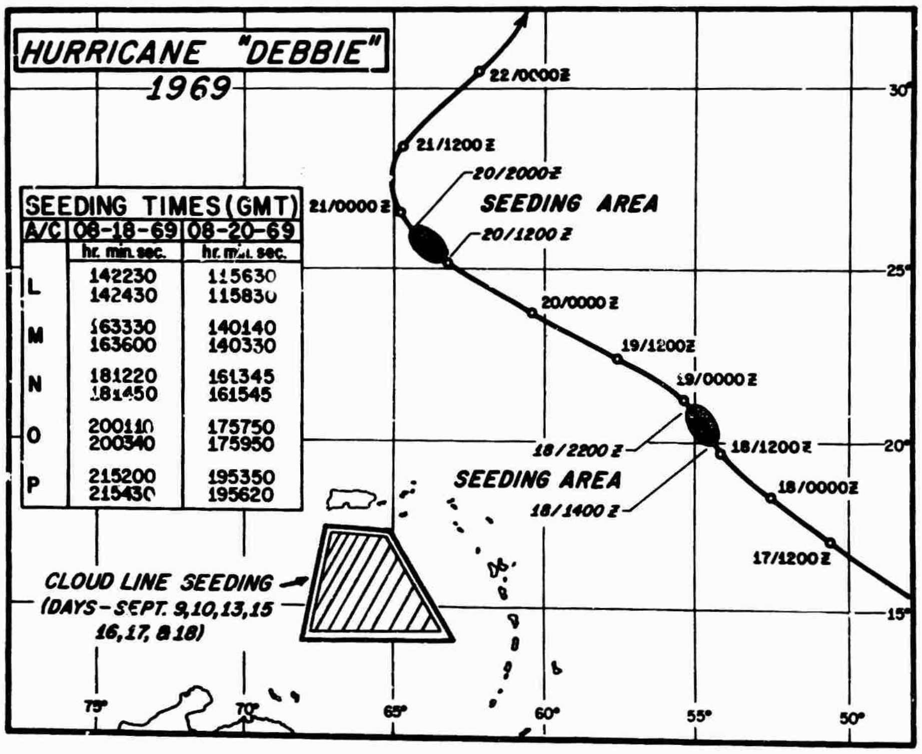

Figure 2. Track of Hurricane Debbie and the periods during which seeding was conducted.

Because of the apparent success of the 1969 seeding experiments conducted in Hurricane Debbie, a great amount of national and international interest has been focused on Project STORMFURY.

In later sections of the report these results and plans for the future will be discussed.

HISTORY AND ORGANIZATION

Project STORMFURY is a joint ESSA-Navy program of scientific experiments designed to explore the structure and dynamics of tropical storms and hurricanes and their potential for modification. It was established in 1962 with the principal objective of testing a physical model of the hurricane's energy exchange by strategic seeding with silver iodide crystals. These crystals have been dispensed by Navy aircraft using Navy-

developed special pyrotechnic devices. The hypothesis calls for reducing the maximum intensity of a storm or hurricane by a measurable amount. Navy and ESSA scientists and aircraft, supplemented by those of the U.S. Air Force, have cooperated in STORMFURY experimental operations since 1962 when the Project began. Until 1969, one mature hurricane (Beulah, 1963) and two series of tropical cumulus clouds (August 1963 and July-August 1965) had been experimentally seeded in the western Atlantic and Caribbean Sea.*

The initial 1962 Project STORMFURY agreement between the Department of Commerce and the Department of the Navy covered 3 years, and it has been renewed annually since then. The 1969 agreement was similar to the 1968 agreement, but was extended to cover 3 years.

Dr. Robert M. White, ESSA Administrator, and Captain E. T. Harding, U.S. Navy, Commander of the Naval Weather Service Command, had overall responsibility for this cooperatively administered project.

The Project Director in 1969 was Dr. R. Cecil Gentry, Director of the National Hurricane Research Laboratory (NHRL), Miami, Florida. The Alternate Director was Mr. Harry F. Hawkins, also of NHRL. The assistant Project Director and Navy Project Coordinator was Commander L. J. Underwood, U.S. Navy, Commanding Officer of the Fleet Weather Facility, Jacksonville, Florida (FLEAWEAFAC JAX). The alternate to the assistant Project Director was Commander J. O. Heft, U.S. Navy, also of FLEWEAFAC JAX. Mr. Clement J. Todd of the Navy Weather Research Facility, Norfolk, Virginia (WEARSCHFAC), was Technical Advisor to the Navy for STORMFURY; Mr. Jerome W. Nickerson, also of WEARSCHFAC, acted as Navy Liaison for Instrument Matters; Dr. S. D. Elliott, Jr., of the Naval Weapons Center, China Lake, was NWC Project Officer; Mr. Max W. Edelstein of the Naval Weather Service Command Headquarters, Washington, D. C., was assigned liaison duties representing the Navy; and Mr. William D. Mallinger of the National Hurricane Research Laboratory was assigned liaison duties for the Project Director and ESSA and acted as Data Quality Control Coordinator.

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* See Project STORMFURY Annual Reports for 1963, 1964, 1965, 1966, 1967, and 1968.

PROJECT STORMFURY ADVISORY PANEL

The Advisory Panel of five members is representative of the scientific establishment and provides guidance through its consideration of various scientific and technical problems. Their recommendations have proved to be of great value to the Project.

The Panel reviews the proposed experiments and their priorities, as well as results from previous experiments. It makes recommendations concerning improving the effectiveness of data collection and evaluation, season length, eligibility criteria for storms to be seeded, and other items as applicable.

During 1969, the Advisory Panel consisted of the following prominent scientists: Dr. Noel E. LaSeur, Chairman (Florida State University), Professor Jerome Spar (Department of Meteorology and Oceanography, New York University), Dr. Edward Lorenz (Department of Meteorology, Massachusetts Institute of Technology), Dr. Charles L. Holser (Dean, College of Earth and Mineral Sciences, Pennsylvania State University), and Dr. James E. McDonald (Institute of Atmospheric Science, University of Arizona). Meetings of the Advisory Panel and representatives of the cooperating agencies were held in Miami, 5 December 1969, and in Washington, D.C. on 9 and 10 February 1970. The panel was thoroughly briefed on the experiments in Hurricane Debbie and on the cloudline experiments conducted this season. They were also kept current on the results obtained from research of the data collected during the seeding experiments. The latest recommendations from the Panel are included in this report as appendix A.

PUBLIC AFFAIRS

The public affairs team plan, implemented in 1967, was continued. The teams, composed of ESSA and Navy public affairs personnel at the staging bases, Miami and Washington, dispensed information to the public on Project STORMFURY. A coordinated press release and fact sheet on plans for STORMFURY were distributed in advance of the hurricane season.

During the seeding of Hurricane Debbie, the requirements of the news media grew fantastically. STORMFURY personnel at the Naval Station, Roosevelt Roads, were kept busy, virtually around the clock, with press releases and answering telephone queries from all over the United States and from places as far away as Honolulu and London. In spite of the amount of

interest and the activity required to satisfy the news media, the plan worked well. Much favorable publicity resulted from these experiments.

During the seedings, two seats on project aircraft were made available on a pool basis to representatives of the media; one to a reporter and the other to a cameraman representing TV networks. This appeared to be sufficient for these operations; however, it is likely that future experiments will evoke even more interest in STORMFURY operations.

PYROTECHNIC DEVICES - SILVER IODIDE

In the 1969 season, the pyrotechnic used was the STORMFURY I unit developed under the leadership of Dr. Pierre St. Amand of the Naval Weapons Center, China Lake. Testing and evaluation of the nucleation effectiveness of the LW-83 compound that this unit contains is continuing. This and other STORMFURY pyrotechnics are discussed in appendix B of last year's STORMFURY Annual Report (1968) and in appendix D of this report. For the cloudline experiments the project used the STORMFURY III pyrotechnic unit. Its characteristics are more fully discussed in the "Field Operations - Cloudline Experiments" section of this report and in appendix D.

AREAS OF OPERATIONS

Eligible areas for experimentation in 1969 were the Gulf of Mexico, the Caribbean Sea, and the southwestern North Atlantic region (see fig. 3).

Operations in these areas were limited by the following guidelines: a tropical cyclone was considered eligible for seeding as long as there was only a small probability (10 percent or less) of the hurricane center coming within 50 mi of a populated land area within 24 hours after seeding.

There are two primary reasons for not seeding a storm near land. First, a storm seeded further at sea will have reverted to "nature's own" before affecting a land mass. Second, marked changes in the structure of a hurricane occur when it passes over land. These land-induced modifications would obscure the short-range effects produced by the seeding experiments and greatly complicate the scientific evaluation of the results.

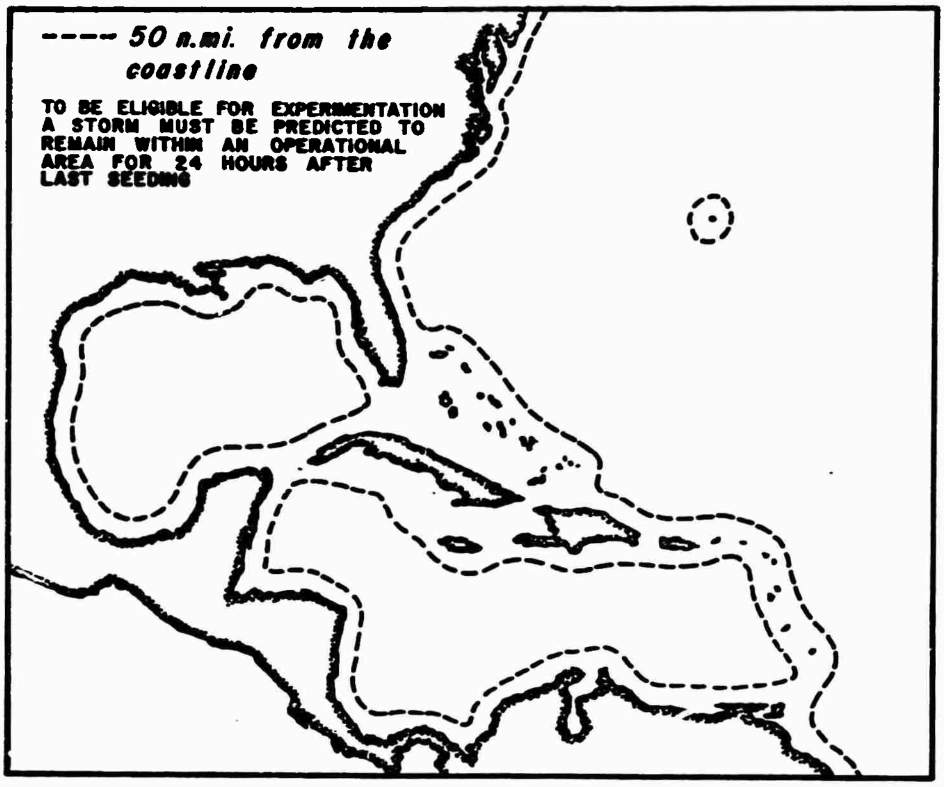

Figure 3. Project STORMFURY operational area.

PLANS FOR FIELD OPERATIONS - 1969

The period 4 August through 15 October was established for STORMFURY operations in 1969. The following aircraft were maintained in readiness:

1. Navy Weather Reconnaissance Squadron FOUR - four WC-121N's.

2. Navy Attack Squadron ONE SEVENTY-SIX - five A-6 Intruders.

3. ESSA Research Flight Facility - two DC-6's, one B-57, one C-54.

4. Air Force, 53rd Weather Reconnaissance Squadron - one WC-130 and one WB-47.

The Operations Plan No. 1-69 was adapted from that of 1968, but was extensively revised to make it much simpler and more convenient to use. The plan specified details of the flight operations; communications; instrument calibration and use; data collection, distribution and archiving; logistic and administrative procedures; airspace reservations agreements; and public affairs.

As recommended by the Advisory Panel, Project officials gave a higher priority to the seeding of hurricane rainbands and cloudlines this season than in previous years, but the eyewall multiple seeding experiment was to be accomplished whenever an opportunity arose.

In accordance with these priorities, a cloudline experiment was scheduled for 9-19 September in the military operational areas near Puerto Rico.

Plans also provided for a series of fall-back research missions when no eligible hurricane or cloud system was available after deployment of Project forces. These would be primarily data-gathering and storm-monitoring operations in unseeded storms.

The multiple seeding of the eyewall experiment calls for five seedings of the clouds around the eye at 2-hour intervals. Each seeding consists of dropping 208 pyrotechnic units along an outward radial flight path, starting just outside the region of maximum winds. The hypothesis states that the introduction of freezing nuclei (silver iodide crystals are produced by the pyrotechnics) into the clouds in and around the eyewall should cause a chain of events that includes the release of latent heat, warming of the air outside the central core, changes in temperature and pressure gradients, and a reduction in the maximum winds. Data from several cases may be needed, however, before definite conclusions can be reached. Because the magnitude of natural variations in hurricanes is sometimes as large as the hypothesized artificially induced changes, it is difficult to distinguish between the two.

The rainband is an important link in the hurricane's circulation system and may prove to be the best region in which to attempt hurricane modification. Research findings suggest that a redistribution of energy in the rainbands could lead to modification of the storm itself.

The cloudline experiment may provide vital data to help understand the dynamics of clouds organized into systems, such as rainbands. It is important to know whether and to what

extent modification of groups of clouds will affect other clouds in the same or nearby lines. These experiments can be conducted when there are no hurricanes and should provide opportunities for improving our understanding of seeding effects and for testing seeding procedures.

Project STORMFURY field experiments are very complex operations that require extensive planning. At times during a multiple seeding experiment, as many as 10 aircraft are operating in the hurricane's circulation. Safety of the aircraft and personnel is paramount in conducting the experiments successfully. Considering the high winds, torrential rains, mountainous seas, and turbulent conditions under which these operations are carried out, it is obvious that training, professionalism, and dedication are vital to safe and successful operations. Radars and communication equipment must be completely reliable. The seeder aircraft must be carefully vectored to their seeding runs by both radar and voice communication. Teamwork is a must. For these reasons it is necessary that the Project stage dry-run rehearsals before actual hurricane experiments to test equipment and procedures and to train the crews.

FIELD OPERATIONS - DRY RUNS

Dry runs were conducted at the Naval Air Station, Jacksonville, Florida, on 29, 30, and 31 July, with a general briefing held on 28 July. Participating in these dry runs were aircraft from the Navy Weather Reconnaissance Squadron FOUR (VW-4), Jacksonville, Florida; five aircraft from Navy Attack Squadron ONE SEVENTY-SIX (VA-176), Oceana, Virginia; and the U.S. Air Force 53rd Weather Reconnaissance Squadron, Ramey AFB, Puerto Rico. The Environmental Science Services Administration's Research Flight Facility (RFF) was unable to participate in the dry run because its personnel had just returned from extensive operations in the BOMEX experiments.

Also taking part were scientists from the Naval Weather Service Command Headquarters, Washington, D.C.; Naval Weapons Center, China Lake, California; Navy Weather Research Facility, Norfolk, Virginia; and ESSA's National Hurricane Research Laboratory.

Although not all the STORMFURY participants were able to attend, the dry runs were considered successful. Coordination and flight patterns were practiced and data sensors and recording equipment tested. All groups performed in an outstanding manner.

FIELD OPERATIONS - HURRICANE DEBBIE

Project STORMFURY personnel went on alert for Hurricane Debbie at 10 A.M. (EDT) Saturday, 16 August, At this time, Debbie was well east of the Lesser Antilles, but was forecast to move in such a manner as to become eligible and within Project aircraft range for experimentation.

Forces commenced deployment on Sunday, 17 August, Four Navy WC-121n's from VW-4, five Navy A-6A jets from VA-176, and two DC-6's from ESSA's Research Flight Facility went to the Naval Station,Roosevelt Roads, Puerto Rico. An Air Force WC-130 and a WB-47 from the 53rd WRS stood by at Ramey AFB, Puerto Rico. Personnel gathered from China Lake, California; Washington, D.C.; Norfolk, Virginia; and Jacksonville and Miami, Florida.

A general briefing for Monday's operation was held at 4:30 P.M. Sunday. Debbie was forecast to be about 650-700 mi from the base at the planned time of the first seeding. This was an extreme range for the operation, but working on Monday, the 18th, insured at least one experiment even if Debbie took an unexpected (but not impossible) turn to the north and moved out of range. It also provided opportunity for a second experiment on Wednesday if the hurricane continued on a northwestern track.

Permission to seed on Monday was requested from and granted by Dr. Robert M. White (ESSA) and Captain E. T. Harding (U.S. Navy).

Flights departed for the hurricane starting at 0500 (GCT) on Monday. Figure 4 shows the on-station times and aircraft planned for the experiment. Considerable additional flight time was required to reach the hurricane and return. Figure 5 shows a seven-level projection of the tracks that were scheduled for the multiple seeding experiment.

Thirteen aircraft made 14 flights and completed all missions close to scheduled time and without major incident. The five Navy A-6 seeder aircraft arrived on station at approximately 2-hourly intervals and released their loads of silver iodide pyrotechnics in the proper regions of the eyewall clouds.

For the 1040 pyrotechnic canisters released by the five seeder aircraft, the firing failure rate was only about 6%.

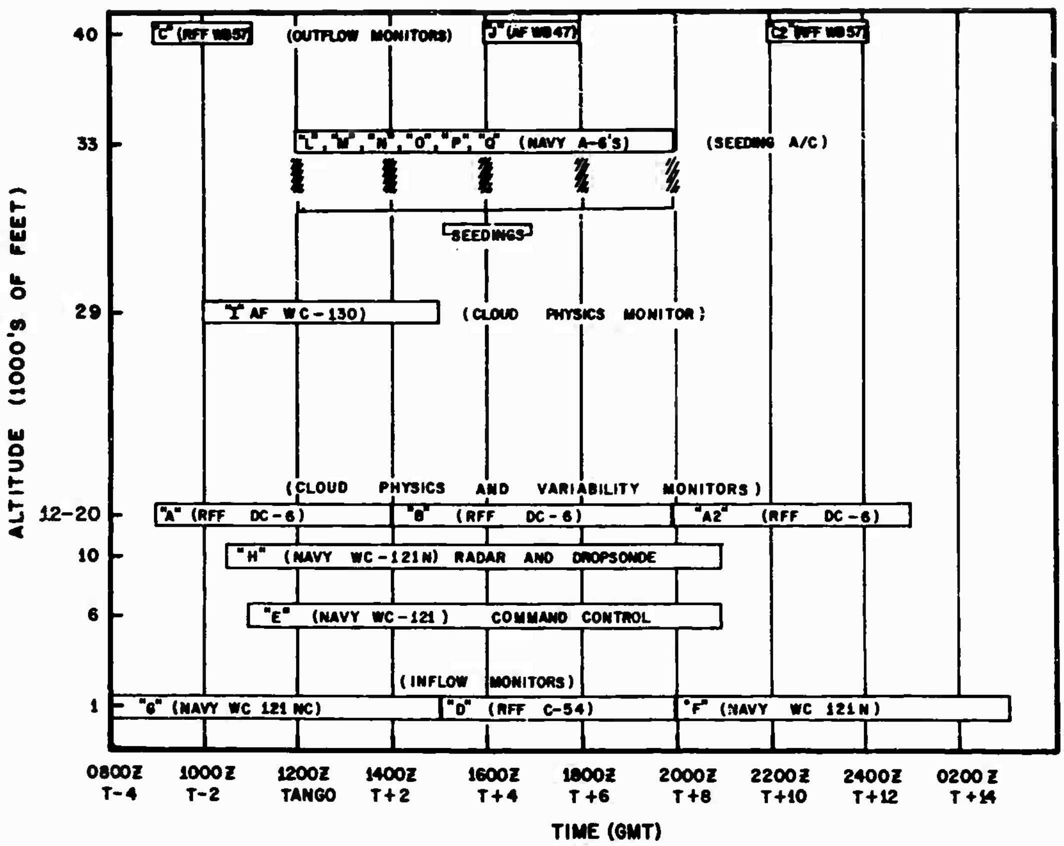

Figure 4. Time table for STORMFURY aircraft deployment - eyewall experiment.

One ESSA DC-6, scheduled to climb to 22,000 feet, lost an engine supercharger and could not maintain this altitude. Its pattern was changed to 12,000 feet (the same as the relieving DC-6) and thus provided almost continuous monitoring of the hurricane at that altitude. One of ESSA's DC-6's completed two 11-hour flights during the experiment and returned at 0700 GCT Tuesday morning, signalling the end of this particular experiment.

The Data Quality Control Coordinator collected the data logs, radar time lapse film, etc., and thoroughly debriefed each flight immediately after landing. See tables 1 and 2 for types of data to be collected by the various flights for the eyewall and rainband experiments.

A general operational and scientific debriefing was held on Tuesday, 19 August, followed by a briefing for the multiple

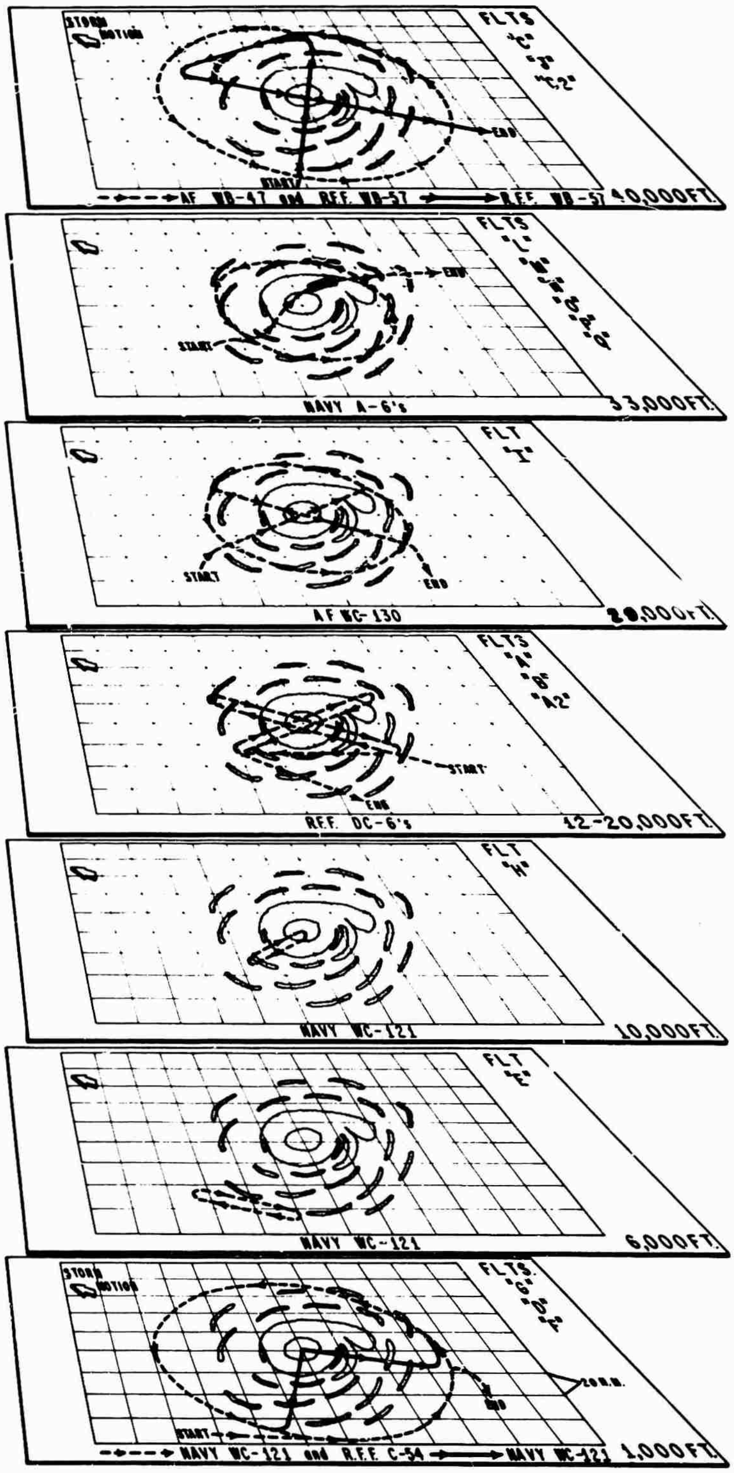

Figure 5. Various flight patterns flown at different altitudes during the eyewall experiment.

Table 1. STORMFURY Data Inventory - Eyewall Experiment.

FLIGHT	A	A2	B	C	C2	D	E	F	G	H	I	J	L	M	N	O	P
SF-1 MET. LOG							X	X	X	X	X						
SF-2 WB-47 LOG												X					
SF-3 SEEDER MET.													X	X	X	X	X
SF-4 RUN REPORT													X	X	X	X	X
SF-5 DAYS OPS													X	X	X	X	X
SF-6 WIND CALIB.	X	X	X			X	X	X	X	X	X	X					
SF-10 MDS LOGS							X	X	X	X							
SF-11 RADARSCOPE LOGS							X	X	X	X			X	X	X	X	X
SF-12 RADAR ADV. LOG	X	X	X			X	X	X	X	X							
AMQ 17 TAPE							X	X	X	X							
NAV LOG	X	X	X			X	X	X	X	X	X	X					
TRUE TRACK RECORD												X					
DIGITAL TAPE	X	X	X	X	X		X	X		X							
PHOTO PANEL FILM	X	X	X	X	X	X											
RADAR FILM						X							X	X	X	X	X
APS-20 FILM (230)	X	X	X				X	X	X	X							
APS-20 FILM (81)							X	X	X	X							
APS-64 FILM												X					
APS-45 FILM							X	X	X	X							
WP-101 FILM	X	X	X														
RDR-1 FILM	X	X	X	X	X												
CLOUD CAMERA FILM	X	X	X	X	X												
DROPSONDES	X	X	X							X	X						
COLD BOX LOG	X	X	X														
MET. LOG (RFF)	X	X	X			X											
RADAR LOG (RFF-5)	X	X	X	X	X	X											
FLIGHT PROG. (RFF-1)	X	X	X	X	X	X											
FLIGHT INFO. (RFF-2)	X	X	X	X	X	X											
FLIGHT DATA (RFF-3)	X	X	X	X	X	X											
DIGITAL STA. (RFF-4)	X	X	X	X	X	X											
DRT. (RFF)	X	X	X			X											
ELECT. STATUS (RFF)	X	X	X			X											
MET. SYSTEMS (RFF)	X	X	X			X											
CLOUD PHOTOS (RANDOM)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
PERSONAL NOTES	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
WWV TIME CHECKS	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
FLIGHT DESIG.	A	A2	B	C	C2	D	E	F	G	H	I	J	L	M	N	O	P
TYPE AIRCRAFT	DC6	DC6	DC6	B57	B57	C54	121	121	121	121	130	B47	A6	A6	A6	A6	A6

Voice Call is STORMFURY plus Flight Letter (STORMFURY Echo). (Each flight turns in the data collected to DQCC as soon as possible after landing.)

Table 2. STORMFURY Data Inventory - Rainband Experiment.

FLIGHT	A	B	C	F	F	G	H	I	J	L	M
SF-1 MET. LOG				X	X	X	X	X			
SF-2 WB-47 LOG									X		
SF-3 SEEDER MET.										X	X
SF-4 RUN REPORT										X	X
SF-5 DAY'S OPS.										X	X
SF-6 WIND CALIB.	X	X		X	X	X	X	X	X		
SF-10 MDS LOGS				X	X	X	X				
SF-11 RADARSCOPE LOGS				X	X	X	X			X	X
SF-12 RADAR ADVISOR LOG				X	X	X	X				
AMQ 17 TAPE				X	X	X	X				
NAV LOG	X	X		X	X	X	X	X	X		
TRUE TRACK RECORD									X		
DIGITAL TAPE	X	X	X	X	X	X	X				
PHOTO PANEL FILM	X	X	X								
RADAR FILM									X	X	X
APS-20 FILM (230)	X	X		X	X	X	X				
APS-20 FILM (81)				X	X	X	X				
APS-64 FILM									X		
APS-45 FILM				X	X	X	X				
WP-101 FILM	X	X									
RDR-1 FILM	X	X	X								
CLOUD CAMERA FILM	X	X	X								
DROPSONDES	X	X						X			
COLD BOX LOG	X	X									
MET. LOG (RFF)	X	X									
RADAR LOG (RFF-5)	X	X	X								
FLIGHT PROG. (RFF-1)	X	X	X								
FLIGHT INFO. (RFF-2)	X	X	X								
FLIGHT DATA (RFF-3)	X	X	X								
DIGITAL STA. (RFF-4)	X	X	X								
DRT. (RFF)	X	X									
ELECT. STATUS (RFF)	X	X									
MET. SYSTEMS (RFF)	X	X									
CLOUD PHOTOS (RANDOM)	X	X	X	X	X	X	X	X	X	X	X
PERSONAL NOTES	X	X	X	X	X	X	X	X	X	X	X
WWV TIME CHECKS	X	X	X	X	X	X	X	X	X	X	X
FLIGHT DESIG.	A	B	C	E	F	G	H	I	J	L	M
TYPE AIRCRAFT	DC6	DC6	B57	121	121	121	121	130	B47	A6	A6

Voice Call is STORMFURY plus Flight Letter (STORMFURY Echo). (Each flight turns in the data collected to DQCC as soon as possible after landing.)

eyewall seeding experiment planned for Wednesday, 20 August.

Hurricane Debbie was forecast to be approximately 430 miles from base at first seeding time (1200 GCT). This shorter distance simplified the operation and reduced transit time required to and from the storm.

Once again all 14 flights were completed with 13 aircraft available and the second multiple seeding of the eyewall of a hurricane was successfully completed.

A general debriefing was held the following morning, and the aircraft and personnel then returned to their home bases to go on standby for the next seeding opportunity.

The spirit, teamwork and "can do" attitude of all participants were outstanding. There were numerous incidents of technicians repairing instruments in flight and restoring their data collection capabilities. The Research Flight Facility even managed some fairly significant repairs on the DC-6, 40C, during the 2-1/2 hours allotted for refueling before it was sent back out with a second crew. The Air Force managed to get a second C-130 flight airborne after the flight originally scheduled had to be used to obtain fixes on Debbie for 6 and 12 hours before Tango (seeding) time on Monday. This was especially noteworthy since Hurricane Camille had already made such a heavy drain on reconnaissance resources. The Navy aircraft controllers on the command/control and back-up command/control aircraft (Constellations) did a far better job of directing the seeder aircraft (A-6A) than they had done in the previous practice operations. When radar or communications equipment failed, command was shifted smoothly between the aircraft, and in several cases the equipment was repaired in a remarkably short time.

Naturally, with so much complicated instrumentation and with so many flights, there were outages. Some of the radars were inoperative, or only partly operative at times.

Research reports on the data collected and evaluation of the seeding results are included in appendices B, E, and H.

Additional research studies are continuing and will be published as soon as they are completed.

FIELD OPERATIONS - CLOUDLINE EXPERIMENTS

STORMFURY forces again deployed to the Naval Station Roosevelt Roads, Puerto Rico, on 8 September 1969 for a series of cloudline experiments planned for the period 9-19 September 1969.

Plans had been made to operate either north or south of Puerto Rico in the Atlantic Fleet Weapons Ranges Alpha or Bravo. All were actually conducted in the southern, Bravo, region because most of the suitable cloudlines were found to the south during this period.

After briefings were completed, flights commenced on 9 September 1969.

The cloudline flights were as follows:

Sept.	WC-121N	DC-6	CESSNA 401	WC130
9, 10, 13	2	2	1	1
15	2	2	2	1
16,17	1	1	2	-
18	-	2	2	-

Suitable cloudlines were not available on 11, 12, and 14 September, but on the other days forces were launched to conduct experiments. Of the remaining seven operational days, four (9, 16, 17, 18) were considered good for cloudline experiments while three (10, 13, 15) were marginal for various reasons.

The STORMFURY III pyrotechnic unit used in these cloudline experiments is housed in a Mark 112 photo flash case in the same manner as the STORMFURY I units used in the eyewall seeding experiments. This unit contains approximately 120 g of EW-20 mixture burning for 20 to 30 sec while falling through approximately 2,000 feet. The Cessna seeder aircraft carried two racks, each with 26 units, located just below and aft of the engine nacelles. (See app. D for further information concerning the pyrotechnics.)

The seeding aircraft dropped units into rising towers along the monitored cloudline. Following a period of drops, the seeder would depart the immediate area to permit the monitoring aircraft to penetrate the seeded clouds in the line. In addition to the normal aircraft data collection systems, photographic documentation was used extensively.

Analysis of these data has not been completed. On several occasions it appeared that individual clouds in a line were caused to fuse into a solid line and increase rapidly in size. Much remains to be learned in this area of research.

RESEARCH ACTIVITIES

Research on the data collected during the seeding of Hurricane Debbie and the cloudline experiments has continued throughout the year at the National Hurricane Research Laboratory and at the Navy Weather Research Facility. Studies include analyses of wind fields, temperatures, pressures and clouds (app. B). Photographs made by time-lapse cameras on aircraft radar scopes are also being studied. These studies are concerned with changes with time in eye size and shape (app. E) and wind vectors derived from following echoes on the radar photographs. Comparisons are also being made between the radar data and the satellite pictures available from the ATS-111 satellite during the seeding operations. Other studies are of ice and liquid water content, size and distribution of ice particles and water drops and other cloud physics data collected during some of the STORMFURY flights. (See app. F.)

Dr. Rosenthal of the National Hurricane Research Laboratory is continuing his work with the symmetrical hurricane model and in addition his group has begun the development of an asymmetrical model of the hurricane. The simulation of the seeding experiment conducted with the hurricane model is discussed in appendix C.

OPERATIONAL AND RESEARCH DATA COLLECTION

During the dry run, the eyewall experiments, and the later cloudline experiments, the quality of data collection noticeably improved as experience was gained. Because several radars were partly or completely inoperative, difficulties were still encountered in obtaining all of the radar data needed. These outages were due largely to a shortage of parts with which to effect repairs.

As stated earlier, an ESSA-RFF DC-6 aircraft was configured to collect cloud physics data during the eyewall experiments, but experienced an engine blower failure that prohibited a climb to the necessary altitudes. For this reason,

measurements of liquid and solid water content and particle size and distribution were made at temperatures below 0°C only during the cloudline experiments and in nonexperimental tropical cyclones. (Hurricane Laurie, 19 and 21 October; Hurricane Inga, 30 September and 1 October; and Tropical Storm Kara, 11 October.) Data from these flights are still being processed.

The system used for debriefing in the Hurricane Debbie seeding experiments worked quite well. Each flight was completely debriefed with comments recorded by the DQCC as soon as possible after landing. This debriefing was in addition to a large general one held later (generally on the following day.)

Processing of all STORMFURY film was done by a single processor in Miami. This system worked well, except for delays encountered in obtaining duplicate copies of film.

OUTLOOK FOR 1970

Project STORMFURY operations will be given increased emphasis in 1970.

The season should start in late July and continue through October instead of 1 August to 15 October as in the past. Also under consideration is a change in the seeding eligibility rules to permit seeding if the hurricane will not be within 50 mi of a populated land mass within 18 hours instead of 24 hours after seeding. (Additional information is given in app. G.)

Priorities will be slightly modified in accordance with the Advisory Panel's recommendations (see app. A).

There will be a few changes in forces for 1970. The Air Force has been requested to provide two WC-130 aircraft because the WB-47 provided last year is no longer available. The Air Force may also provide RB-57F aircraft for high altitude photographic coverage of seeding operations. The ESSA-RFF will be receiving a WC-130 type aircraft to replace the C-54 sometime in August or September 1970. The Navy is seeking a P-3 aircraft to be tested during 1970 for its capability as a seeder and cloud physics data collection platform.

Pyrotechnic generators for 1970 are expected to be slightly modified from those used last year. The new unit is called WMU-1 (XCL-1)/B and as yet has no nickname. Its chemical contents, however, are similar to those used in 1969.

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APPENDIX A

RECOMMENDATIONS OF THE ADVISORY PANEL TO PROJECT STORMFURY

February 1970

INTRODUCTION

Without doubt, the major new input for Panel consideration has resulted from the multiple seeding experiments in the eyewall of Hurricane Debbie on 18 and 20 August 1969. Operationally, these experiments were an unqualified success; scientifically, the analyses of the results to date have established that a measurable and significant decrease in wind speed occurred subsequent to the seeding and persisted for several hours after seeding ceased, at least on 18 August. Encouraging as the results may be, the analyses to date do not, and further analysis probably cannot, provide proof that the seeding caused the weakening. Examples of similar decreases in intensity followed by redevelopment can easily be found in past records of nonseeded hurricanes; thus what was observed in Debbie lies within the limits of natural variability, but departs significantly enough from typical behavior to be encouraging. Nor can solid support of cause-and-effect relationship between the seeding and wind speed decrease be supplied from results of current computer simulation of natural and seeded hurricane behavior. Until these model simulations are improved, the results of the calculations cannot be considered definitive. Of course, the present sample of seeded cases is so small as to render statistical estimates of significance highly uncertain.

The Panel would like to emphasize that the potentially enormous national benefits that may someday accrue from systematic mitigation of hurricane damage, even to a small degree, constitute a worthwhile target of the national weather modification program. We believe the experimental results to date to be sufficiently encouraging to warrant further experimentation, but we caution against such premature conclusions that these results constitute a scientific basis that would justify the implementation of an operational seeding program.

The Panel makes the following recommendations at this time, with the objective of focusing attention, financial and material support, and Project effort on those aspects of the program we believe deserve emphasis.

RECOMMENDATION ONE

The Panel recommends that top priority at all required levels be given to the acquisition by the Project of aircraft and instrumentation necessary to obtain accurate and representative observations of liquid and solid water content of the eyewall and vicinity in the layer from approximately 20,000 to 35,000 feet before, during, and after seeding.

Reasons: The fundamental premise of the current eyewall seeding experiments is the existence of significant amounts of supercooled water in this layer and its conversion to ice as a result of the seeding. Measurements of changes in wind speed, pressure profiles, and other parameters cannot demonstrate the truth of this basic premise. Until the type of measurements recommended above has been realized, reasonable doubt as to the foundation of the seeding experiments will continue to exist. Evaluations can thus be based upon the degree of the conversion of the eyewall to ice rather than upon the attempted conversion.

RECOMMENDATION TWO

The Panel recommends continued critical analysis of data collected in association with the experiments in Hurricane Debbie, 18 and 20 August 1969.

Reasons: Every effort must be made to describe and understand as completely as possible the structure of Debbie before and after seeding and to establish association, if not cause-and-effect relationship, between the seeding and observed changes in storm structure.

RECOMMENDATION THREE

The Panel recommends continued monitoring of unseeded hurricanes in a manner similar to that carried out after seeding.

Reasons: Further quantitative data on the natural variability of hurricanes are needed as a background against which to compare the observed behavior of seeded storms. Our knowledge of natural variability remains quite inadequate to properly assess the reality of changes observed. This comparison should not be primarily on a statistical basis, but rather on the basis of physical understanding and its computer simulation.

RECOMMENDATION FOUR

The Panel recommends further expansion of the encouraging efforts of Project personnel in the computer simulation of hurricane structure and behavior.

Reasons: In the past few years interaction between those who have collected and analyzed improved data from hurricanes and those who have attempted computer simulation of these storms has certainly been an important factor in the increased degree of understanding we now have of the structure, formation, and behavior of hurricanes. However, hurricane models remain inadequate in providing realistic simulation of these aspects of the hurricane. Improved computer models combined with better data from both seeded and unseeded storms offer probably the most promising avenue of establishing the validity of modification experiments and further improving our understanding of the hurricane. Increased participation by nongovernment groups in this field of research should be encouraged.

RECOMMENDATION FIVE

The Panel repeats its previous recommendation that preliminary investigation of other possible means of hurricane modification be continued.

Reasons: There is no reasonable doubt that modification of air-sea energy exchange processes should significantly influence the hurricane. Before undertaking field experiments, the magnitudes involved and the logistic feasibility should be assessed.

RECOMMENDATION SIX

Again, the Panel recommends attempts to arrive at an evaluation of the conflicting evidence as to the relative and absolute nucleating effects of the pyrotechnic devices under laboratory conditions, and dissemination of this information in appropriate publications.

Reasons: Although the truly relevant observations must probably be made in the natural atmospheric environment rather than the laboratory, a resolution of current conflicting results should be attempted. If such a resolution is not possible, that result together with the reasons for it, should be disseminated.

RECOMMENDATION SEVEN

The Panel recommends the following priorities be adhered to in executing field experiments during the 1970 season:

First Priority - repetition of the multiple eyewall seeding experiment.

Second Priority - seeding of organized lines of convective clouds, either in the form of a "rainband" associated with a hurricane or tropical cyclone, or a "cloudline" associated with tropical disturbances of lesser intensity.

Reasons: It is imperative that final priority be given to attempts to duplicate the encouraging results obtained from the first multiple eyewall seeding experiments. Within the limits of available logistic capability, however, the Panel encourages cloudline and rainband seeding experiments. These should be attempted on any occasion when project personnel and equipment have been assembled for a potential eyewall experiment that had to be aborted, and in other circumstances, at the discretion of the Project directors.

RECOMMENDATION EIGHT

The Panel continues to recommend that preparation for field operations include a "dry-run" exercise in which all personnel and equipment are checked out. Actual cloudline seeding experiments could be executed as part of such a dry run.

Reasons: It is obviously desirable that new personnel and equipment be checked out before an actual experiment. Past experience with such dry runs clearly demonstrates their value. The addition of actual cloudline seeding experiments would further motivate participants and yield valuable data at little additional investment.

RECOMMENDATION NINE

The Panel recommends the following changes in eligibility criteria for seeding experiments, in order that the probability of such experiments be increased:

(a) the period during which such experiments may be carried out to be extended to 1 July - 1 November, and

(b) the time interval before which the hurricane is forecast to affect a populated land area with a probability greater than 10% be decreased from 24 to 18 hours.

<u>Reasons</u>: Evaluation of experience with the current selection criteria, and assessment of the proposed criteria for climatological data, suggest a small but useful increase in experiment probability would result without increased risk.

RECOMMENDATION TEN

The Panel renews its previous recommendation that planning for the Project consider longer-term (approx. 5 years) considerations with further increases in support.

<u>Reasons</u>: This recommendation is perhaps implicit in the previous nine, but it is considered worthwhile to make it more explicit. The Panel believes the Project to be in a position to solidify present results and to extend these significantly if appropriate support and planning were available.

Dr. Noel E. LaSeur, Chairman
Dr. Charles L. Hosler
Dr. Edward N. Lorenz
Dr. James E. McDonald
Dr. Jerome Spar

APPENDIX B

THE HURRICANE MODIFICATION PROJECT: PAST RESULTS AND FUTURE PROSPECTS

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Atlantic Oceanographic and Meteorological Laboratories
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Miami, Florida

INTRODUCTION

Results from Hurricane Debbie modification experiments on 18 and 20 August 1969 are so encouraging as to offer hope that man may one day exert a degree of control over the intensity of these devastating storms that originate over the tropical oceans. These were the first multiple hurricane seeding experiments ever conducted by STORMFURY or any other group. Earlier modification experiments have been reported by Simpson and Malkus (1964).

Two general considerations justify Project STORMFURY experiments: (1) recent improvements in our understanding of the physical processes fundamental to the maintenance of hurricanes suggest good avenues of experimentation, and (2) enormous rewards can be derived from even a slight degree of beneficial modification. The first will be elaborated in later sections; the second may be illustrated by the following rough "cost-benefit" analysis.

Hurricanes caused an average annual damage in the United States of 13 million dollars between 1915 and 1924. By the period 1960 to 1969, this figure had jumped to 432 million dollars. Even after adjusting these values for the inflated cost of construction in recent years, this represents a 650% increase in the average annual cost of hurricane damage in less than than 50 years (Gentry, 1966). Since Americans are constructing more and more valuable buildings in areas exposed to hurricanes, these damage costs should continue to increase. Hurricane Betsy of 1965 and Hurricane Camille of 1969 each caused more than 1.4 billion dollars in damage. If the United States continues supporting hurricane modification research at the present rate for the next 10 years and if by that time we modify just one severe hurricane, such as Betsy or Camille, sufficiently to reduce its damage by only 10 percent, the nation will have a 1000 percent return on its investment. The benefits

in terms of prevention of human suffering are, of course, incalculable.

At least two fundamentals established in recent years by studies of hurricane structure and maintenance suggest avenues for beneficial modification: (1) an internal energy source is necessary if a hurricane is to reach or retain even moderate intensity; this source is the sensible and latent heat transferred from the sea surface to the air inside the storm, and (2) the energy for the entire synoptic-scale hurricane is released by moist convection in highly organized convective scale circulations located primarily in the eyewall and major rainbands. In the first, we find an explanation of the observations that hurricanes form only over warm tropical waters and begin dissipating soon after moving over either cool water or land, neither of which provides a flux of energy to the atmosphere sufficient to keep the storm at full intensity In the second, we find a more rational explanation of the low percentage of tropical disturbances that become hurricanes. If a warm sea with its large reservoir of energy were the only requirements, we would have 5 to 10 times as many hurricanes as normally form. During the 1967 and 1968 hurricane seasons, 130 tropical waves were tracked in the Atlantic and adjacent areas where sea surface temperatures were warm enough for hurricane genesis, but only 13 of the areas developed storms of full hurricane intensity (Simpson et al. 1969). If, however, there are only a limited number of ways in which the convection and synoptic scales of motion can interact to achieve optimum utilization of the energy flowing upward from the ocean, then it is not surprising that few tropical disturbances intensify and become hurricanes.

THEORY OF MODIFICATION

Both of the above findings suggest possible field experiments that may beneficially modify a hurricane. On the basis of the first, we may attempt to reduce the flux of energy from the sea surface to the atmosphere, probably through attempts to inhibit evaporation. On the basis of the second, we may try to modify the release of latent heat in the small portion (2 to 5%) of the total storm occupied by the organized active convective-scale motions in a manner that redistributes heating to produce a weakening of the storm.

We do not now know of any practical means of reducing the flux of energy from the sea surface to the atmosphere in the gale and hurricane force winds.

We do have a means of modifying the rate of release of latent heat in the clouds of the hurricane. This we can do by introducing freezing nuclei into the clouds containing supercooled water drops. By causing them to freeze, we could add heat to the air in the storm. The question to be answered is where in the storm could addition of heat result in a reduction in the maximum winds. This is particularly pertinent because the hurricane is a heat engine. It derives its enormous energy by converting latent and sensible heat extracted from the ocean and the warm moist tropical air into potential and then partially into kinetic energy. We have sought the answer to this question by theoretical investigation and numerical modelling work.

The life cycle of hurricanes can now be simulated by theoretical mathematical models. Researchers at ESSA and at a number of universities have been developing these models for a number of years (Ooyama, 1969; Rosenthal, 1970). Current models are capable of simulating only an axially symmetric cyclone with rather limited vertical resolution and they parameterize in a relatively simple fashion the effect of air-sea interaction and the transfer of energy by cumulus convection. They cannot predict the effects on storm motion of artificial intervention. They do, however, simulate many features of a hurricane quite well.

We have used the model developed by S.L. Rosenthal (1970; also app. C) to get indications of where to release the heat by seeding the supercooled clouds with freezing nuclei (silver iodide). We have also asked what effect the seeding might have on the intensity of the hurricane. The answer to the first question is to release the heat just outside the mass of relatively warm air concentrated in and around the core of the hurricane. Specifically, the best chance for reducing the maximum intensity of the hurricane is to seed from the core of the belt of maximum winds outward along a radius. The model suggests that this can result in a reduction of maximum winds in the hurricane by about 15 percent.

THE MODIFICATION EXPERIMENT

The modification experiment, therefore, seeks to exploit energy sources within the hurricane. Hurricane clouds contain large quantities of water substance still in the liquid state at temperatures lower than -4°C (fig. B-1). Introduction of silver iodide nuclei at these and lower temperatures should cause the water droplets to change to ice crystals and release the latent heat of fusion, thus providing a possible mechanism for adding heat to the hurricane. One objective of the STORMFURY

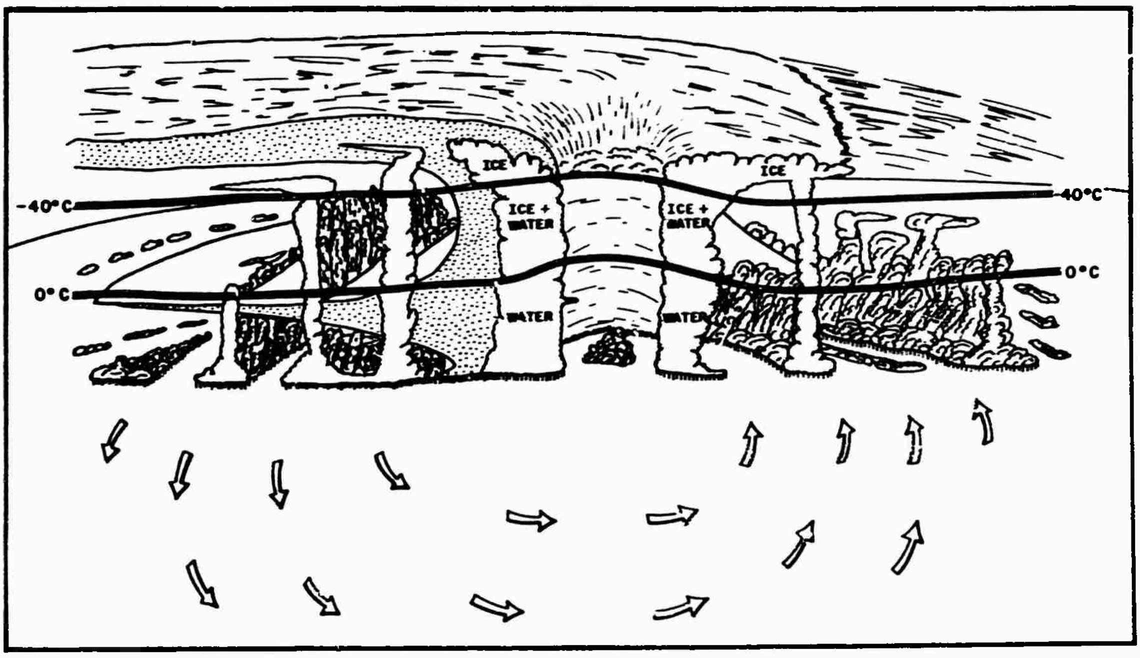

Figure B-1. Schematic cross section of a hurricane.

experiments is to verify indications from the numerical model that heat should be released at the outer edge of the mass of warm air occupying the central portion of the hurricane in order to cause a reduction in the storm's intensity. The experiments on Hurricane Debbie were designed to determine if addition of heat in this area would result in diminishing the maximum horizontal temperature gradients in the storm and, eventually, in weakening the maximum winds of the storm.

HURRICANE DEBBIE EXPERIMENT

Hurricane Debbie was a mature storm with winds stronger than 100 knots on 18 August. It was about 650 nautical miles east-northeast of Roosevelt Roads, Puerto Rico, the primary operating base of Project STORMFURY (fig. B-2). This was an extreme range for the experiment, but other conditions were favorable and the storm was moving west-northwestward so that its course would bring it closer to the base as the day progressed. Thirteen aircraft were available -- nine from the Navy, two from ESSA, and two from the Air Force. Five aircraft carried the pyrotechnics for seeding the hurricane with silver iodide, and the others monitored the storm for changes in structure and intensity beginning about 6 hours before the first seeding and continuing until 6 hours after the fifth and last seeding.

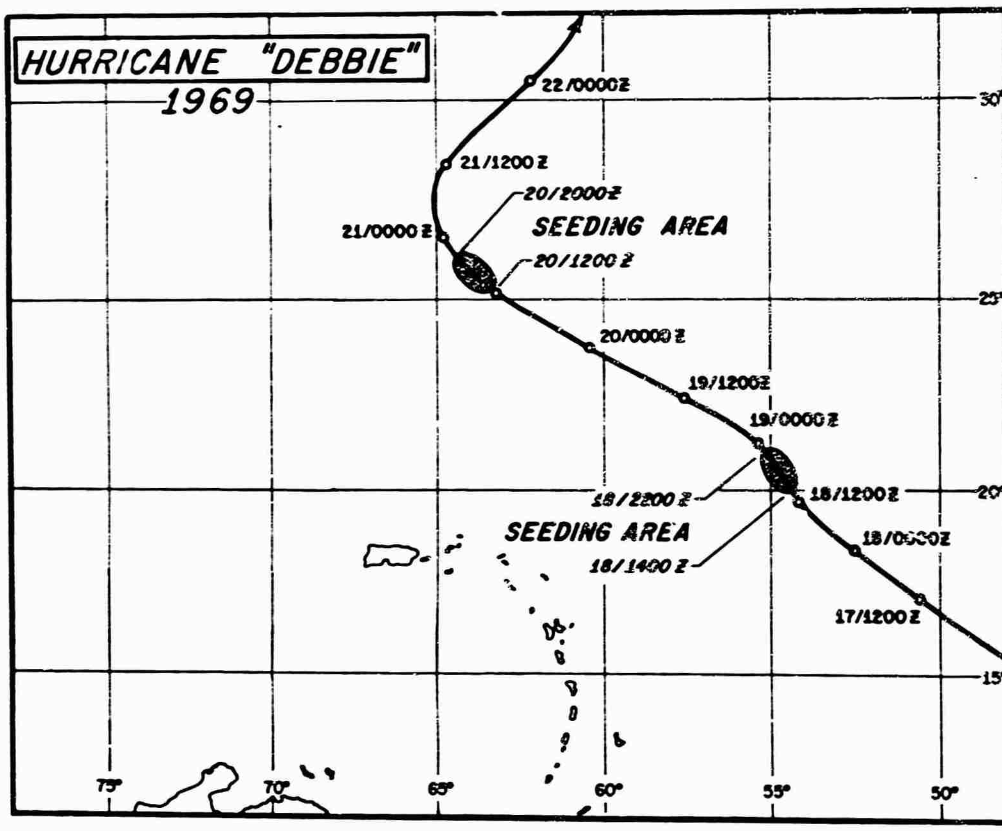

Figure B-2. Track of Hurricane Debbie, August 1969. Seeding areas on 18 and 20 August are indicated on the track.

The Navy seeder aircraft approached the storm from the south-southwest at 33,000 feet, penetrated and crossed the eye, and entered the wall cloud on the north-northeast side. Shortly after entering the wall cloud and at a spot where past experience suggests one should cross the radius of maximum winds as well as the most intense temperature gradients, the crew started dropping the pyrotechnic generators that produced the silver iodide. Each aircraft carried 208 of these and dropped them along a line leading radially away from the center (fig. B-3). Each generator contained 190 g of silver iodide and each gram should produce in excess of 10^{12} freezing nuclei. There is some evidence that each gram might produce more than 10^{14} nuclei active at temperatures found in the hurricane clouds (Elliot et al. 1969; also app. D).

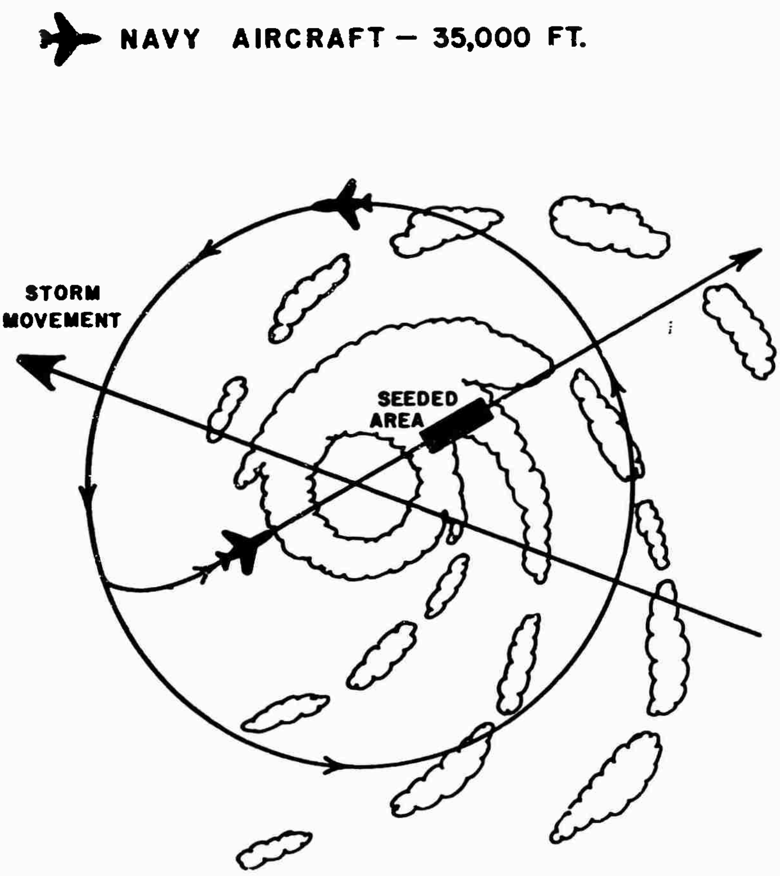

Figure B-3. Track of seeder aircraft.

Each seeding run lasted 2 to 3 min or between 14 and 20 n mi. The five seeding runs came at intervals of approximately 2 hours on each of the 2 days.

On the 20th, the first seeder aircraft flying at 30,000 feet commenced its dropping run after circling in the eye. Upon entering the eyewall clouds it experienced extremely strong downdrafts which forced the aircraft down to 27,000 feet. Release of the generators was made during the descent but close to the proper location.

No other seeder flights on either experimental day encountered turbulence that could be considered more than light or briefly moderate.

DATA FOR EVALUATING THE EXPERIMENTS

Many data were collected by personnel in the monitoring flights and some by the five seeder aircraft. The most detailed information was collected at 12,000 feet by the two DC-6 aircraft of ESSA's Research Flight Facility. They have similar instrumentation systems which have been cross-calibrated and have crews trained in using the same techniques. Data from the two aircraft are as nearly comparable as planning and testing can make them. These aircraft were assigned to relieve each other in making repetitive passes across the storm, in order to provide almost continuous coverage of the hurricane by one of them from 3 hours before the first seeding until 5 or 6 hours after the fifth one. This was essentially accomplished, except for some time gaps on 18 August when the storm was at such great range that the first aircraft could not make the round trip to base for refueling during the time the second aircraft could remain on station. In previous mature hurricanes such as Debbie where we have made measurements at several levels, the 12,000-foot winds have been about 95 percent as strong as those near the surface (Hawkins, 1962).

The flight patterns called for each aircraft to make a round trip across the storm from a point about 50 n mi east-southeast of it or to a point beyond the belt of strongest winds. Each aircraft then flew similar traverses from the south-southwest quadrant to the north-northeast quadrant until fuel shortage dictated departure from the storm. Since we have more data on the later passes, they are the ones presented in figures B-4 and B-5. In most cases with a storm moving west-northwest the strongest winds are found a short distance north-northeast of the center.

RESULTS AND DISCUSSION

Between successive passes on both the 18th and 20th, the winds sometimes increased and sometimes decreased. In the mean, however, the wind speeds decreased from shortly after the second seeding until at least 5 or 6 hours after the fifth seeding. This decrease was most marked on the 18th (fig. B-4).

Before the first seeding on 18 August, maximum winds at 12,000 feet were 98 knots. By 5 hours after the fifth seeding they had decreased to 68 knots, or by 31 percent. The storm re-intensified on 19 August, starting about 8 hours after the last seeding on the 18th. On 20 August the maximum wind speed before the first seeding was 99 knots. Within 6 hours after the final seeding the maximum had dropped to 84 knots, a decrease of 15 percent.

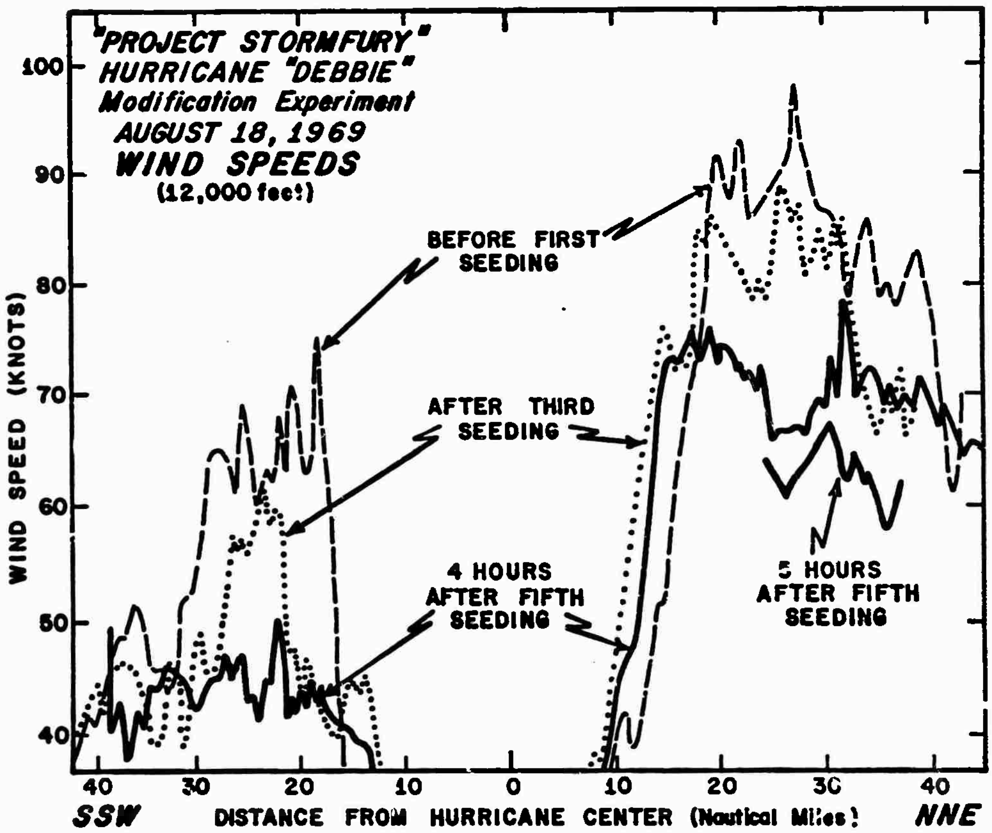

Figure B-4. Changes with time of wind speeds at 12,000 feet in Hurricane Debbie on 18 August 1969. The winds were measured by aircraft flying across the storm from south-southwest to north-northeast or the reciprocal track. Profiles are given that show the wind speeds before the first seeding, after the third seeding, and after the fifth seeding.

The response of the winds to the seeding on 20 August was more impressive than this summary suggests. Debbie had a double wall cloud structure on this day. That is, there were two concentric walls with radii of approximately 10 and 20 n mi, respectively. Each was associated with a maximum of wind speed at corresponding radii. The hypothesis for the experiment calls for the nuclei to be introduced into clouds at greater radial distance than that of the maximum winds. All the seedings were so conducted relative to the inner maximum, but only the fifth seeding was performed beyond the outer maximum. The wind speeds of the inner maximum started decreasing after the second seed-

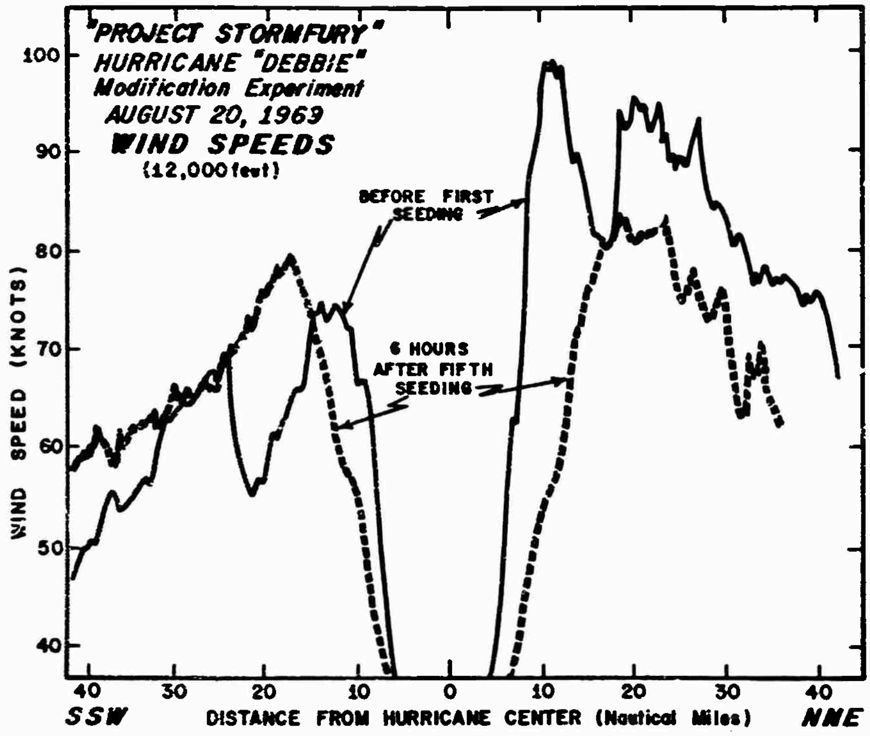

Figure B-5. Same as fig. B-4, except that the wind speed profiles are for 20 August 1969 and are for the periods before and after the seedings.

ing, but the outer maximum did not show a net decline until after the last seeding.

Variations in the force of the wind are closely related to variations of the square of the wind speed or the kinetic energy of the air particles. These decreases in maximum winds represent a reduction in kinetic energy in the belt of maximum winds of 52 and 28 percent, respectively, on 18 and 20 August.

That Hurricane Debbie decreased in intensity following multiple seedings on 18 and 20 August is well established. What we do not know is whether the decrease was caused by the seeding, or whether it represents only natural changes in the hurricane.

From analyses of past storms, we can, however, make some statements as to the probability that the changes observed might have occurred naturally. The rate of rise in central pressure in Debbie that accompanied the reduction in wind speed

on 18 August has occurred in only 9 percent of 502 periods of similar length we have studied in other tropical cyclones. Our measurements of winds in previous hurricanes are less complete than are those of pressure changes, but it is believed that the rate of decrease in wind speeds on 18 August is a relatively rare event.

Although the decrease in wind speeds on 20 August was smaller than on 18 August, this rate of decrease occurs in considerably less than one-half of the hurricane days. Furthermore, on each of the days, the reduction in wind speed occurred at a time when it could reasonably have been caused by the seeding experiment.

Rough agreement between results from the simulated seeding experiment with the numerical model (app. C) and those from Hurricane Debbie gives some support to the hypothesis that the seeding caused a reduction in Debbie's maximum winds. The model experiment, M2, suggests that the reduction in sea-level winds would begin about 4 hours after initiation of the simulated seeding and would continue until about 4 hours after seeding ceased. This is approximately what happened on 18 and 20 August in the Debbie experiments. The model simulation experiment indicated that the reduction of maximum winds at sea level would be about 15 percent. The Debbie experiments gave reductions of 31 and 15 percent at 12,000 feet. Considering the many unknowns in both the model and the field experiments, this agreement should certainly be considered satisfactory if not remarkable. It is clouded, however, by the fact that the model experiment did not indicate as much as 15 percent reduction in the maximum wind speeds at 700 mb, which is the level in the model closest to 12,000 feet (see app. C).

Analyses of other data collected on Debbie give some support to the hypothesis that the hurricane was modified by the seeding. In most hurricanes the diameter of the eye varies directly with the radius of the maximum winds. Since experiments with the theoretical model suggest that there would be an increase in the radius of maximum winds, we investigated changes in the structures of the hurricane eye and the clouds surrounding it.

Airborne radar photographs of Hurricane Debbie, taken on 18 and 20 August 1969, were used to measure the echo-free area within the eye (see app. E). Results for the 18th show sudden increases in echo-free area 1 1/4 hours after seeding time for several of the seedings.

Results for the 20th were quite different. The most obvious evidence on that day suggesting seeding effects was the

rotation rate of the major axis of the elliptical eye. A reduced rate of rotation occurred within 10 min after each seeding. This was followed 1 1/2 hours later by a rapid increase in the rotation rate, which continued until the next seeding time. The period of the cycle (the time required for one complete revolution of the major axis) was about 2 hours, which was the approximate interval between seedings.

Based on a limited number of cases for nonmodified storms, it seems likely that these changes observed in Debbie's radar images are relatively rare.

We can conclude that changes in maximum wind speeds and other items related to structure of Hurricane Debbie were appreciable following modification attempts on 18 and 20 August. Study of past storms reveals that the changes come within the range of natural variability. The data are certainly very suggestive, however, that the experiment caused some modification in the storm.

FUTURE PLANS

The thing that seems obvious is that since results of the 1969 modification attempts suggest so strongly that modification was accomplished, the experiment must be repeated on one or more additional storms as soon as practical to seek further confirmation. We must also continue searching for clues from the data still to be analyzed, and from results of our theoretical investigations in order to better identify probable cause and effect relationships and to improve design of our seeding experiments.

The various groups supporting STORMFURY are proceeding with preparations that will make it practical to do the multiple seeding experiment on four different hurricane days during the 1970 season if nature provides the opportunities. In addition, other experiments are planned for use when a hurricane is not satisfactory for the big experiment. These involve seeding the bands of clouds spiraling around the hurricane, and seeding them at distances greater than 40 n mi from the center of the hurricane. At these radii the thermal structure and lapse rates in clouds are very different from those nearer the center of the hurricane. The objective of seeding these outer clouds would be to make them become more active and offer competition to those nearer the center. It is believed that in this manner the energy of the storm could be distributed over a larger area and not be as intense in the area of principal concentration.

A dry run will be performed in July to check out new procedures suggested by the Debbie experiments and to train the new crews that will be participating in the modification experiment for the first time. This will be followed by some experimental seedings of clouds arranged in lines but in circulations not related to a tropical cyclone. This will provide opportunity to study not only the effect of seeding on individual clouds but also the interaction between adjacent clouds when both are seeded. Knowledge thus gained should be applicable to the design of modification experiments on the tropical storms and hurricanes to be seeded later in the summer.

ACKNOWLEDGMENTS

I wish to express deep appreciation and pay tribute to all those who have contributed to the success of STORMFURY. These include the Navy, Air Force, and ESSA crews who made the field experiments on Hurricane Debbie a success; members of the National Hurricane Research Laboratory and other agencies who have assisted in the research; and the STORMFURY Advisory Panel. The work herein reported has indeed been the result of a team effort.

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APPENDIX C

A CIRCULARLY SYMMETRIC, PRIMITIVE EQUATION MODEL OF TROPICAL CYCLONES AND ITS RESPONSE TO ARTIFICIAL ENHANCEMENT OF THE CONVECTIVE HEATING FUNCTIONS

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INTRODUCTION

Over the past few years, a primitive equation model that simulates the development and structure of tropical cyclones with a fair degree of reality has been developed at the National Hurricane Research Laboratory (Rosenthal, 1970a, 1970b). While the primary motivation for this work has been to increase understanding of hurricane dynamics, we have also realized that such a model would have some value for testing and evaluating various experiments that have been suggested for trial in hurricane modification. The calculations discussed below were aimed at testing a variant of the hypothesis presented by Simpson and Malkus (1964).

The first few experiments carried out with the model during the early spring of 1968 suggested that a slight variant of Simpson's and Malkus' proposal might be worthy of consideration. These calculations showed that during (unmodified) intensification of the model storm, maximum heating (nominally associated with the "eyewall") was located at a significantly smaller radius than was the surface wind maximum. As development proceeded, the wind maxima moved inward more rapidly than did the heating maxima. Invariably, development ceased, and decay began when the heating maxima and the surface wind maxima became nearly coincident. The implication of this sequence of events, at least for the model storm, is that heating at radii less than that of the surface wind maximum is favorable for intensification and that the reverse is true for heating at radii greater than that of the surface wind maximum.

Some seeding simulations performed in 1968 seemed to verify this notion. However, at that time, the model was very crude and preliminary compared with its current form. When the "seed-

ing" was done at radii greater than that of the surface wind maximum, we found decreases in intensity of greater magnitude and of longer duration than those observed when the 'seeding" crossed the maximum winds (Gentry, 1969). In both cases, however, the "seeding" was at radii greater than that of the strongest "natural" heating. The results of these calculations were used as guidance material for planning the 1969 field experiments (Gentry, 1969).

The calculations in 1968 were intended to simulate "single seeding" field experiments in which the seeder aircraft discharges its material once in a pass of 2 to 3 min covering a radial interval of about 30 km. Those involved in the field program (Gentry, 1969) were of the opinion that a single seeding experiment could release heat of fusion over the 500- to 300-mb layer equivalent to a heating rate of 2°C per 30 min and lasting for 30 min. At 300 mb, this amounts to freezing about 2.5 g of water per cubic meter per half hour. At 500 mb, the figure is approximately 4 g of water per cubic meter per half hour.

To simulate this process, the heating function that represents the cumulus feedback on the macroscale (Rosenthal, 1969) was simply increased by the amount and for the period cited above at selected radii.

The author is well aware that substantial uncertainty exists concerning the "true" heat of fusion released in such experiments and recognizes the obvious need for further observations and experiments aimed at establishing these freezing rates. Because of this uncertainty, because of the extremely crude manner in which the seeding is simulated, and for still other reasons to be cited later, results obtained from the model must not be taken too literally; at best they should be considered guidance material.

Processed data from the 1969 field experiments on Hurricane Debbie became available in October 1969 and have been summarized elsewhere (Gentry, 1970; also app. B). On both days significant decreases in wind speed at the 12,000-foot level were observed. On August 18, the wind maximum at the 12,000-foot level decreased by about 30 knots after the seeding was completed.

As part of the effort aimed at determining the extent to which the observed changes could be attributed to intervention by man, we attempted simulations of multiple seeding experiments of the Debbie type. Results are presented below.

REVIEW OF THE MODEL

As already noted, between the 1968 and the 1969 seeding simulations, the model had been substantially improved. A recent report (Rosenthal, 1970b) discusses these changes in detail; hence, only a brief summary is presented here.

The vertical structure of the atmosphere is represented at seven levels with geometric height as the vertical coordinate. These levels correspond to pressures of 1015, 900, 700, 500, 300, 200, and 100 mb in the mean tropical atmosphere. All variables are defined at all levels. Circular symmetry is assumed, and the primitive equations are employed. External gravity waves are eliminated through a simplification of the continuity equation. The radial limit of the computational domain is 440 km, and the system is open at this lateral boundary. Boundary conditions here require the horizontal divergence, the vertical component of the relative velocity, and the specific humidity to be zero.

The model simulates convective precipitation (and the macroscale heating due to this latent heat release) as well as the enrichment of the macroscale humidity due to the presence of the cumuli. Convection may originate in any layer, provided the layer has a water vapor supply from horizontal convergence and conditional instability exists for parcels lifted from the layer. Nonconvective precipitation is also simulated.

With the exceptions cited here, the version of the model used for the 1969 seeding simulations is identical to the one described earlier (Rosenthal, 1970b). The original model simulated the air-sea exchanges of sensible and latent heat through the requirement that temperature and relative humidity at the lowest two levels (1015 and 900 mb) be steady state and horizontally uniform. This pragmatic restraint is still present in the calculations discussed before (Rosenthal, 1970b). However, by November 1969, when the new seeding simulations were performed, the program had been generalized to include explicit predictions of the air-sea exchanges of sensible and latent heat.

In summary, changes in the model between the 1968 and 1969 seeding simulations consisted of (1) addition of the explicit water vapor cycle and the nonconvective precipitation, (2) simulation of convection that originates above the boundary layer, (3) improvement of the surface drag formulation, (4) inclusion of the explicit predictions of air-sea exchanges of sensible and latent heat, and (5) refinement of the radial resolution from 20 to 10 km.

Despite the fact that this model is one of the more sophisticated of the circularly symmetric models in existence and that it has provided extremely realistic results (Rosenthal, 1970b) it does suffer from two major deficiencies. The first is the highly pragmatic parameterization of cumulus convection (Rosenthal, 1970b). Substantial improvements in this area must await increased understanding of both cumulus convection and its interaction with macroscale flows.

The second major difficulty comes from the assumption of circular symmetry and precludes direct comparison between model calculations and specific real tropical cyclones. The latter are strongly influenced by interactions with neighboring synoptic systems, and these vary markedly in character from storm to storm. The model results must, therefore, be considered representative of some sort of average cyclone.

Despite this, some interesting comparisons between the seeding simulations described below and the field experiment are found elsewhere in this report and show a number of areas in which the model behaves in a fashion similar to the observed behavior of Hurricane Debbie. There are, of course, also areas in which the model calculation and the field experiments show significant differences.

THE CONTROL EXPERIMENT

The major characteristics of the control calculation selected for this purpose (Experiment S18) are summarized below. This experiment differs from one already published (Rosenthal, 1970b) only in the more general treatment of air-sea exchanges of sensible and latent heat as described in the previous section.

Figure C-1 summarizes the sea-level history of Experiment S18. Deepest central pressure and strongest winds occur at 168 hours. These peaks, however, appear to represent "overshooting" of an equilibrium state and, as shown below, a closer approach to a steady state occurs between 192 and 216 hours. As we have noted in previous papers (Rosenthal, 1969, 1970a 1970b) the vertical motion at 900 mb is an excellent measure of the convective heating in the model. From the bottom section of figure C-1, therefore, it is clear that the relationship between the radius of maximum heating and that of the strongest surface winds is as described in the introduction. i.e., during the growth stage; strongest heating is at a radius smaller than that of the strongest surface winds. After maximum intensity is reached, the inverse appears to be the case.

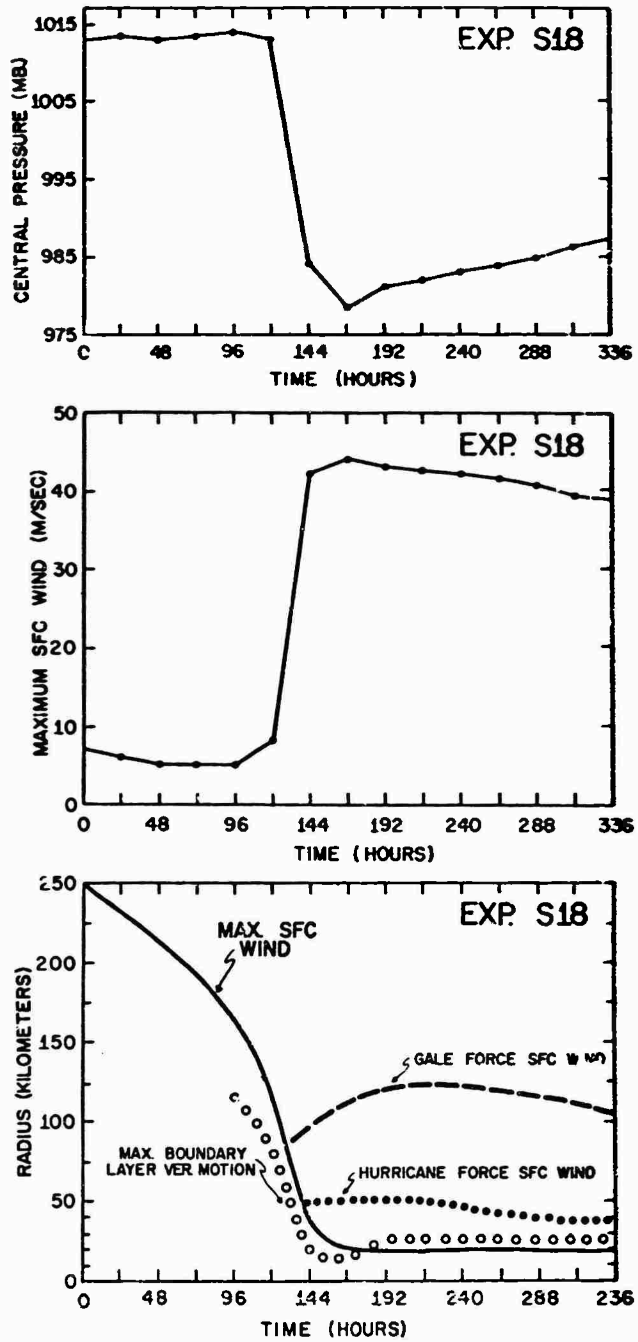

Figure C-1. *Results from Experiment S18. Top: Central pressure as a function of time. Center: maximum surface wind as a function of time. Bottom: Radii of maximum surface wind; outer limit of hurricane and gale force winds at the surface. Radii of maximum 900-mb vertical motion.*

Figure C-2, which shows detailed histories of several variables during the 192- and 216-hour period, verifies the near-steady state of the model storm at this time. The net change in central pressure is less than 1 mb, while the surface wind maximum changes by less than $1 m\text{-}sec^{-1}$. An oscillation with a period of about 8 hours appears in the data, but the amplitude is quite small. In the 700-mb winds, where the amplitude appears greatest, it is less than $0.5\ m\text{-}sec^{-1}$.

Figures C-3, 4, 5, and 6 further verify the near-steady state of the model storm during the period of interest. The 8-hour oscillation is clearly also present in the 300-mb temperatures (fig. C-5) and the boundary layer vertical motion (fig. C-6).

Figures C-7 through 10 provide additional information concerning the structure of the model storm at hour 192 but may be considered representative of the entire period of 192 to 216 hours.

PROCEDURES FOR THE SEEDING SIMULATIONS

The heating rates for the seeding simulations were established after discussion with Dr. Gentry. These consultations revealed that he continued in his belief that 2°C per 1/2 hour was the correct heating rate for a single seeding. However, he was now of the opinion that the effect would be felt for at least 1 hour (in contrast to the half hour cited at the time of the 1968 calculations). It was also Dr. Gentry's belief that the enhanced heating might be more or less continuous over the 10-hour period spanned by a multiple seeding operation of the Debbie type.

The seeding simulations may be distinguished from each other, therefore, on the basis of three characteristics:

(1) Whether the enhanced heating function is applied continuously or intermittently.

(2) The radii at which the enhanced heating is applied.

(3) The magnitude of the enhanced heating.

As for the 1968 calculations, the heating function is enhanced only at the 300- and 500-mb levels, the levels in the model that are in the layer seeded in the field experiment. For enhanced heating of the intermittent type, the heating functions were increased during 192-193 hrs, 194-195 hrs,

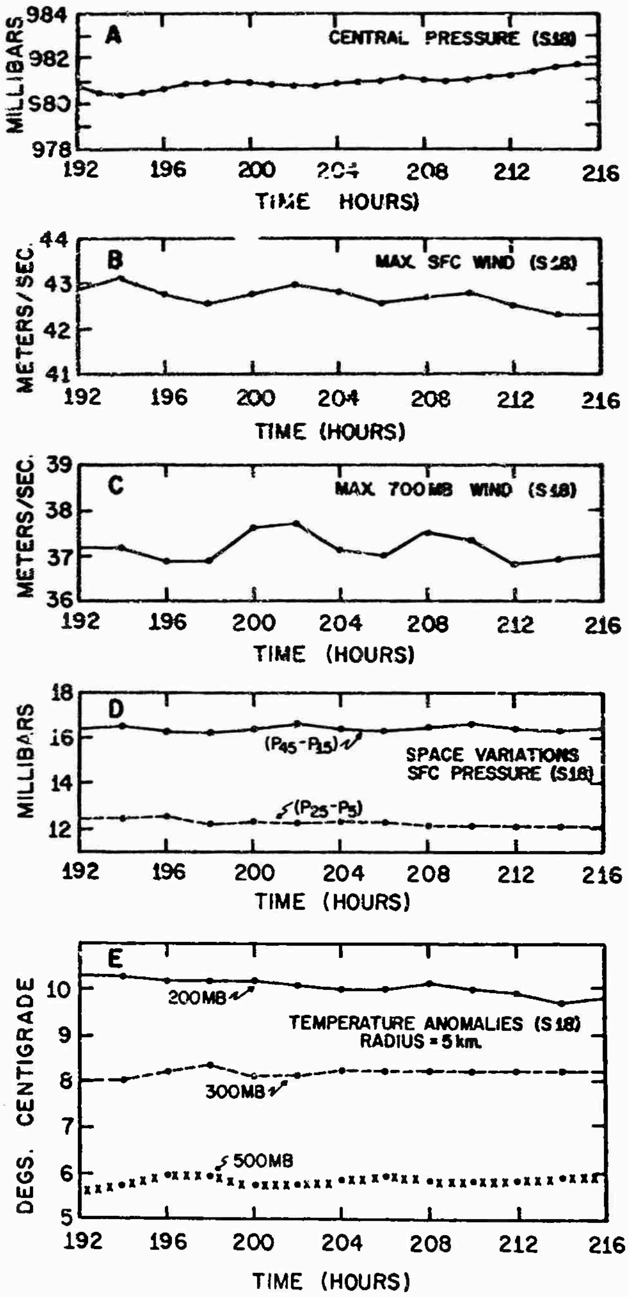

Figure C-2. Results from Experiment S18. Time histories of: (A) Centra pressure, (B) maximum surface wind, (C) maximum 700-mb winds, (D) surface pressure differences between 45 and 15 km (solid) and between 25 and 5 km, and (E) temperature anomalies at 5 km radius, 200 mb (solid), 300 mb (dashed), and 500 mb (XXX).

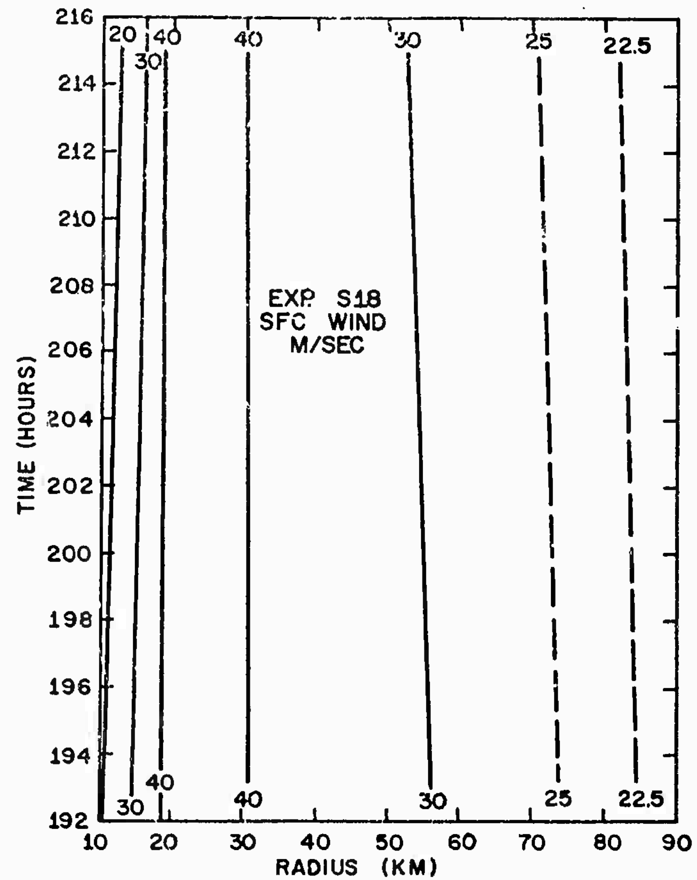

Figure C-3. *Results from Experiment S18. Time-radius cross section of surface wind speed.*

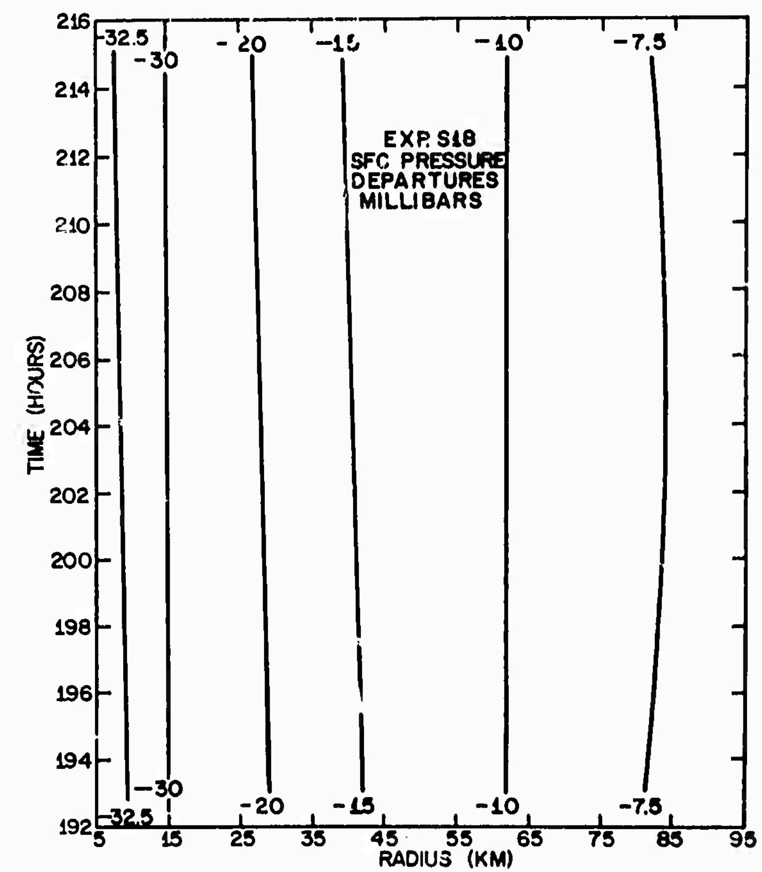

Figure C-4. *Results from Experiment S18. Time-radius cross section of the departures of surface pressure from 1015 mb.*

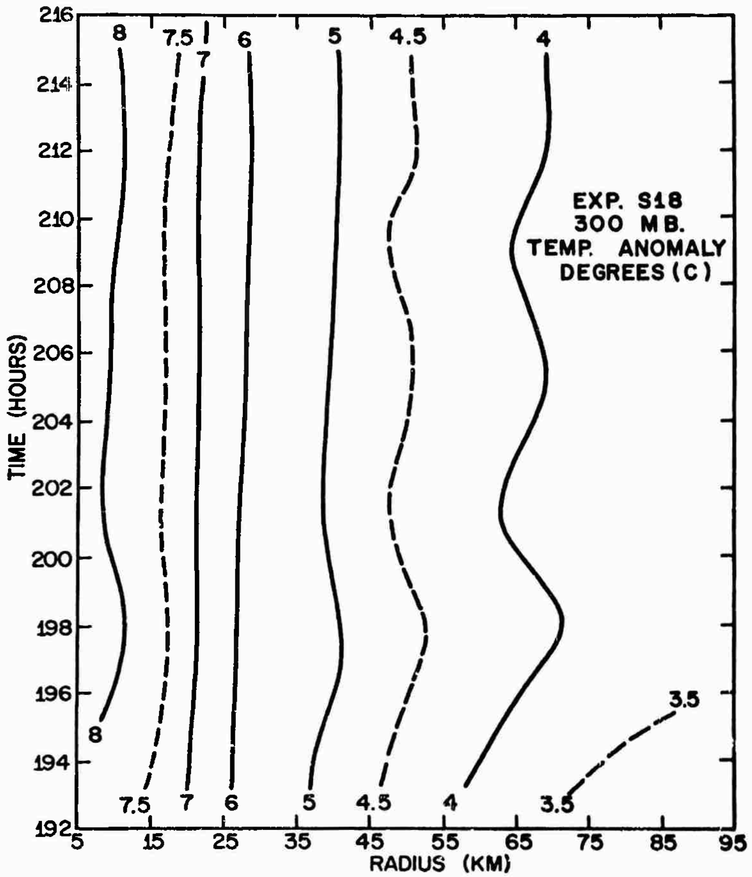

Figure C-5. Results from Experiment S18. Time-radius cross section of 300-mb temperature anomalies

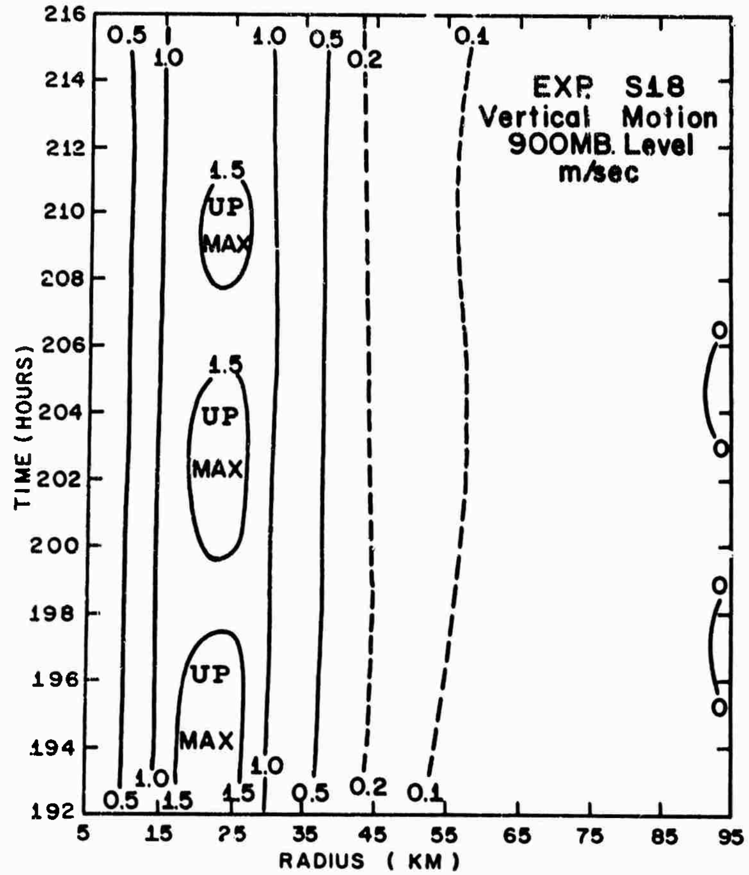

Figure C-6. Results from Experiment S18. Time-radius cross section of 900-mb vertical motion.

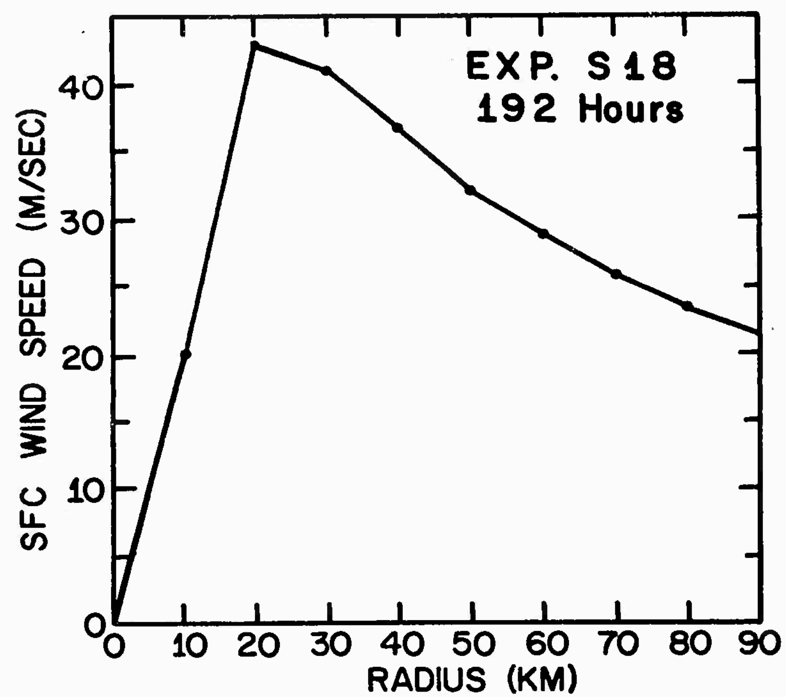

Figure C-7. *Results from Experiment S18. Radial profile of surface wind speed at 192 hours.*

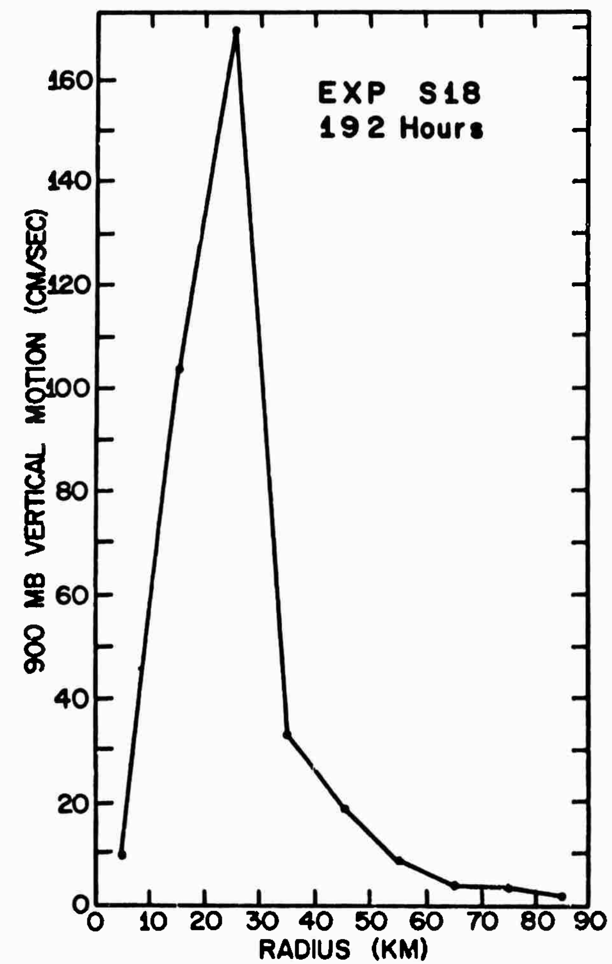

Figure C-8. *Results from Experiment S18. Radial profile of 900-mb vertical motion at 192 hours.*

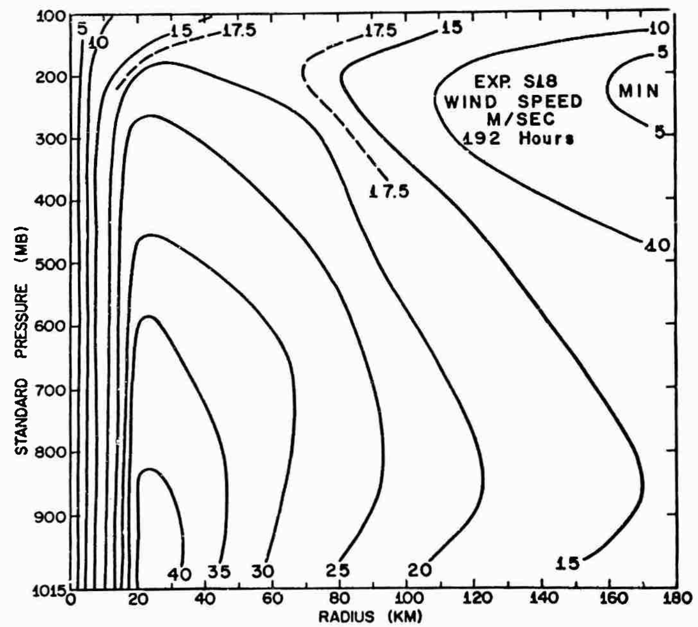

Figure C-9. *Results from Experiment S18. Cross section of total wind speed at 192 hours.*

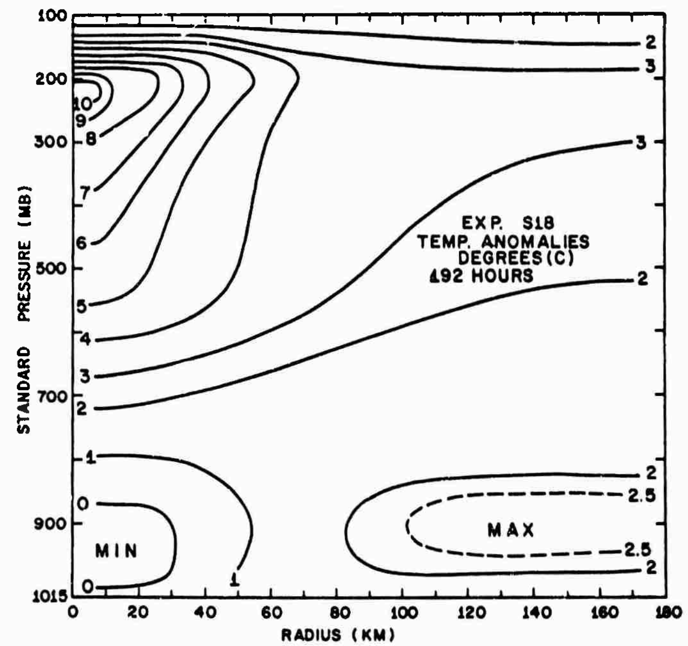

Figure C-10. *Results from Experiment S18. Cross section of temperature anomaly at 192 hours.*

196-197 hrs, 198-199 hrs, and 200-201 hrs. For continuous enhanced heating, the heating function was increased by a fixed amount over the period 192-202 hrs. Differences between calculations with continuous and intermittent enhancement are relatively minor. As a consequence, results shown are only for continuous heating.

Experiments in which the "seeding" radii are varied are distinguished by the terms "small" and "large" radii experiments. In the small radii experiments, heating is enhanced at 25, 35, and 45 km. Since the natural heating is greatest at 25 km (see fig. C-8), these calculations contain enhanced heating at the natural maximum as well as at the next two grid points with larger radii. In large radii experiments, heating is enhanced at 35, 45 and 55 km, which is clearly beyond the radius of largest natural heating. In both types of experiments, enhanced heating is at radii larger than that of the surface wind maximum (compare figs. C-7 and 8).

Experiments in which the magnitude of the enhanced heating is varied are referred to as "normal", "large", and "extreme" heating cases. In the normal heating experiments, the heating function is increased by an amount equivalent to 2° per 1/2 hour. For large and extreme heating experiments, the enhancement is by 6° per 1/2 hour and 9° per 1/2 hour, respectively.

CONTINUOUS, NORMAL HEATING AT SMALL RADII (EXPERIMENT M1)

Figure C-11 compares surface wind profiles with the control. During the first 4 hours of enhanced heating, the surface winds tend to become slightly more intense than the control, particularly at radii just beyond the center of the "seeded" region. After 8 hours of enhanced heating (fig. C-11B), a new surface wind maximum has formed at 40 km and the wind has decreased by about 3 m sec^{-1} at the radius of the original maximum. At the new maximum, the wind is about 5 m sec^{-1} greater than the control, and beyond 30 km the modified storm is everywhere more intense than the control. At 204 hours (fig. C-11C), which is 2 hours after the termination of the enhanced heating, the new maximum has become slightly less intense by about 5 m sec^{-1} and continues to decrease in intensity (as do all the winds between radii of 20 and 70 km) until 208 hours. This is undoubtedly a result of the storm having come into some sort of balanced state with the enhanced heating, which is then upset when the "seeding" is terminated. At 208 hours, at the radius of the original maximum, the modified storm shows surface winds less by about 1 m sec^{-1} than those of the control. The maximum of the modified storm (at 40-km radius)

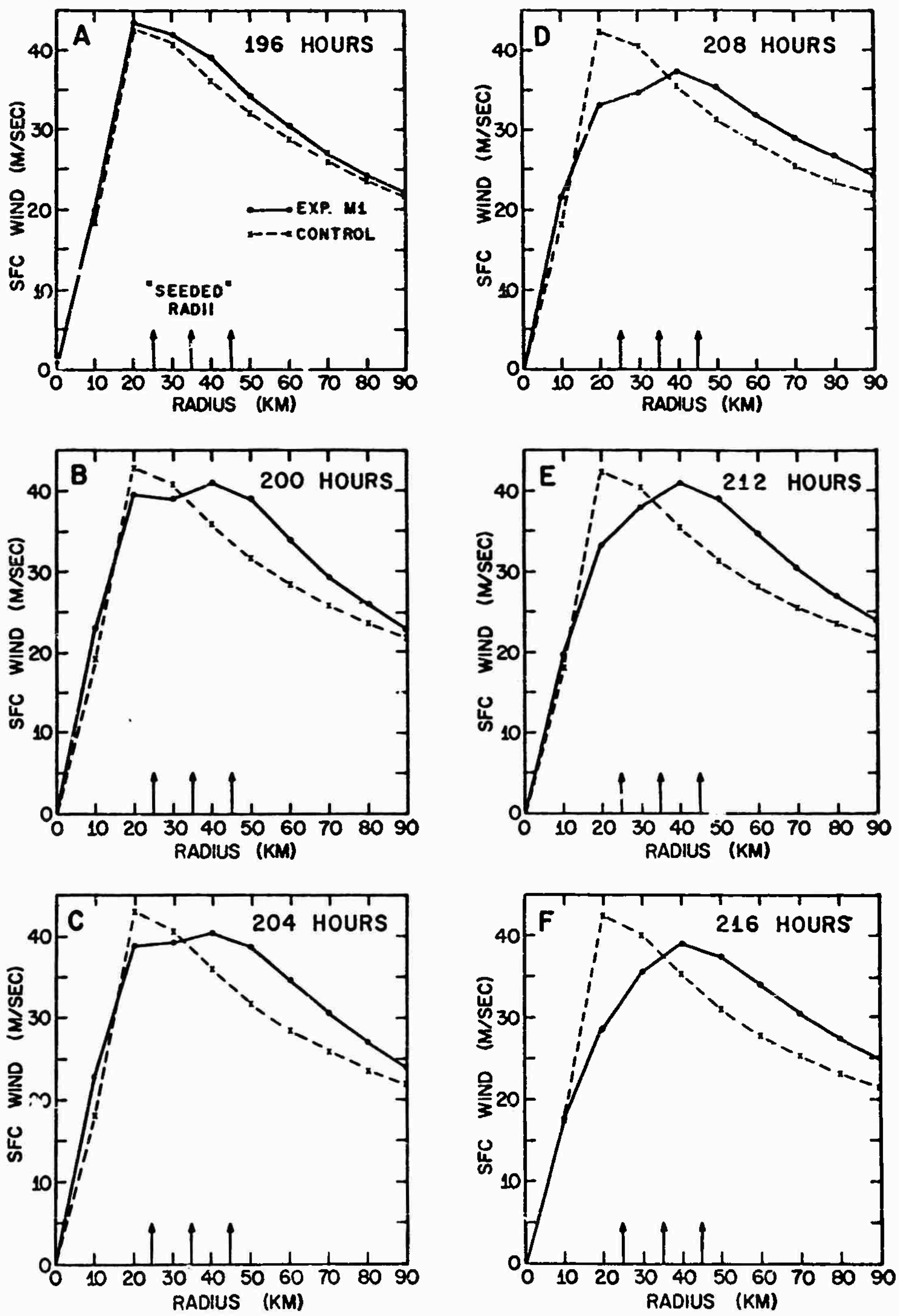

Figure C-11. Results from Experiment M1. Comparison of surface wind profiles with the control experiment (S18) as a function of time. Dashed arrows indicate grid points at which enhanced heating was applied.

is about 5 m sec^{-1} less than the maximum for the control. However, substantial portions of the "seeded" storm continue to show winds stronger than those of the control.

Figures C-11D through F show the new wind maximum at 40 km to be a stable feature of the modified model storm. The decrease in intensity noted between 204 and 208 hours does not continue indefinitely, and the system appears to oscillate in an attempt to find a new equilibrium. At 216 hours, winds at the 20-km radius are about 14 m sec^{-1} less than those of the control. However, the maxima for the two experiments differ by only about 3 1/2 m sec^{-1}.

At 700 mb (fig. 12), intensification during the first 4 hours is significantly greater than at the surface, presumably because of the absence of the moderating effects of surface drag. By 200 hours, a new 700-mb wind maximum is established at 50 km, and, in contrast to conditions at sea level, the new maximum is stronger*(by about 3 1/2 m sec^{-1}) than that of the control. At the radius of the new maximum, 700-mb winds are about 10 m sec^{-1} greater than those of the control. While the sense of the evolution of the 700-mb data is more or less similar to that found at the surface, only at 208 hours (6 hours after the termination of the enhanced heating) is the maximum in the modified storm less than that of the control.

In summary, figures C-11 and 12 show the evolution of the wind field to be in some degree similar to that predicted by the slight variant of the Simpson hypothesis suggested in the introduction. The wind maxima do establish themselves in fairly stable configurations at larger radii and with less intensity. However, beyond 30 to 40 km, surface winds become more intense than those of the control. When the enhanced heating is terminated, winds tend to decrease. However, this decrease is not persistent, and the modified storm oscillates apparently in an attempt to find a new balanced state. The evolution at 700 mb is similar, but here the initial intensification is greater, and during most of the calculation the 700-mb wind maximum is stronger than that of the control. However (see footnote), the latter factor may be due to grid spacing.

The histories of these wind maxima as well as those of the central pressure are summarized in figure C-13. The central

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*The configuration of the control 700-mb profile indicates that with finer resolution the results at this level might change significantly.

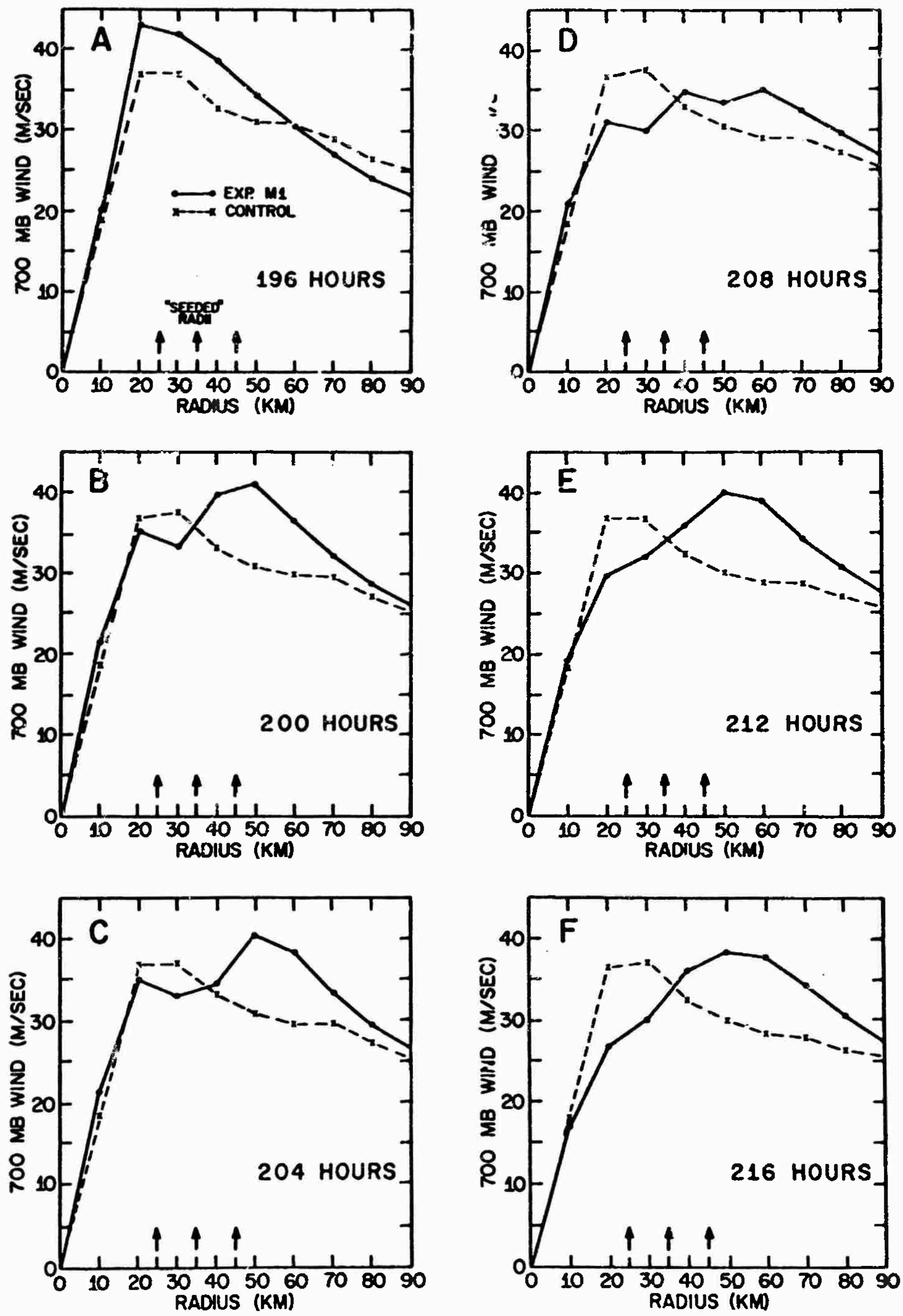

Figure C-12. Results from Experiment M1. Comparisons of 700-mb wind profiles with those for the control experiment (S18) as a function of time. Dashed arrows indicate grid points at which enhanced heating was applied.

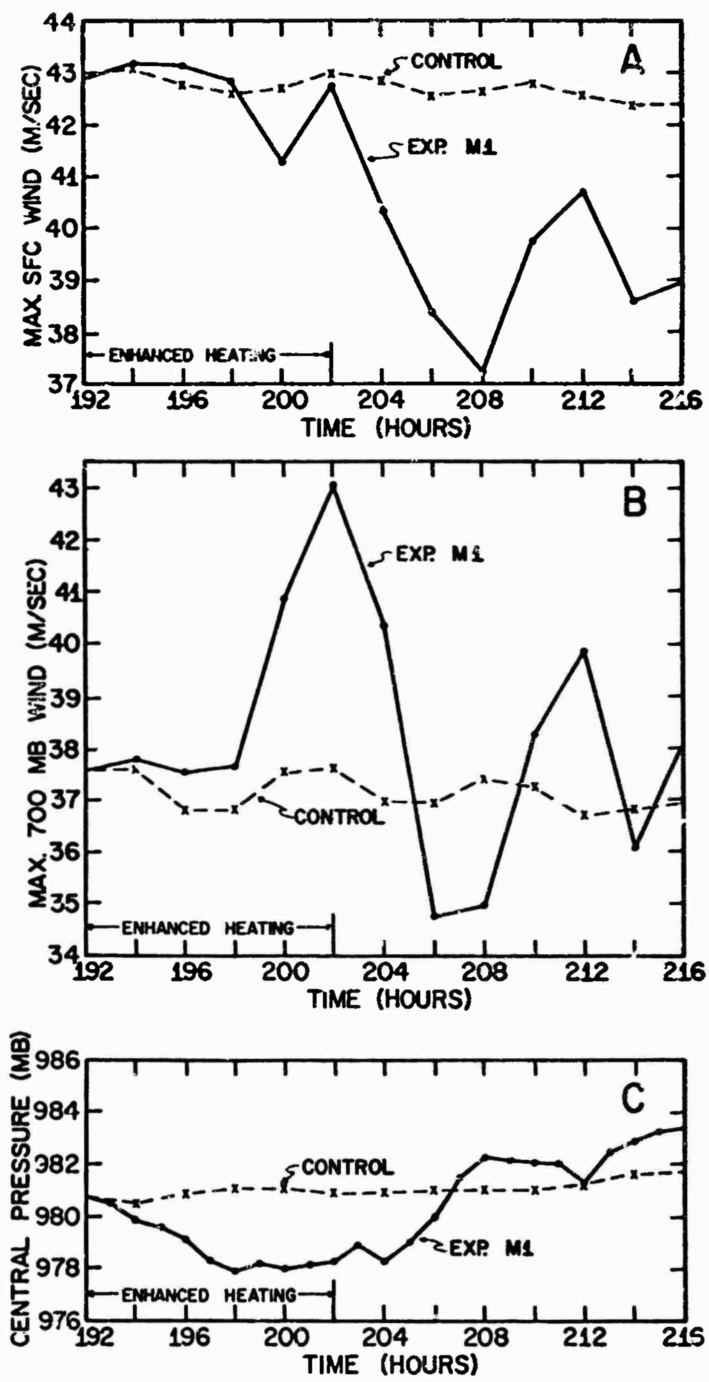

Figure C-13. Comparisons of time histories of Experiment M1 with those of the control: (A) surface wind maxima, (B) 700-mb wind maxima, and (C) central pressure.

pressure decreases during the period of the enhanced heating and begins to increase only after the "seeding" is terminated and even then is never more than about 1.5 mb greater than the control. The evolution of the 300-mb and 500-mb temperatures (figs. C-14A and B) at the midpoint of the "seeded" region (35-km radius) shows rather small increases, which never exceed 2°C. However, the radial temperature gradients are reduced substantially (figs. C-14C and D) and the surface pressure gradient is correspondingly reduced (fig. C-14E).

Figure C-15 (compare with fig. C-6) shows that the maximum low level vertical motion shifts outward to a radius of 35 km and increases slightly in strength until the enhanced heating is terminated. Thereafter, it remains fixed at the new location while oscillating in magnitude.

CONTINUOUS, NORMAL HEATING AT LARGE RADII (EXPERIMENT M2)

Experiment M2 was also conducted with normal and continuous heating, but the enhancement was at large radii. At this heating rate, the differences between heating enhancement at small and large radii were small, but in the sense predicted by the arguments in the introduction.

EXPERIMENTS WITH EXTREME HEATING

Two experiments are of prime interest in this section:

(1) Experiment M5 (continuous, extreme heating at small radii).

(2) Experiment M6 (continuous, extreme heating at large radii).

Figure 16 compares surface wind maxima for these calculations with those for Experiment M2. A surprising aspect of the figure is the tendency for the three results to approach each other near the end of the calculations, despite the fact that enhanced heating in Experiments M5 and M6 is nine times that for M2. The major differences are in the first few hours when the strength of the wind maximum for M6 (extreme heating, large radii) decreases dramatically and then increases in an equally dramatic fashion. The surface wind profiles for Experiment M5 behave very much like those for M1 and M2 (fig. C-17). In M6 however, the original surface wind maximum is destroyed very rapidly. The sharp reduction in surface wind at 194 hours of M6 (fig. C-16) represents a transition period in which the original maximum has been weakened and the new maximum has not yet

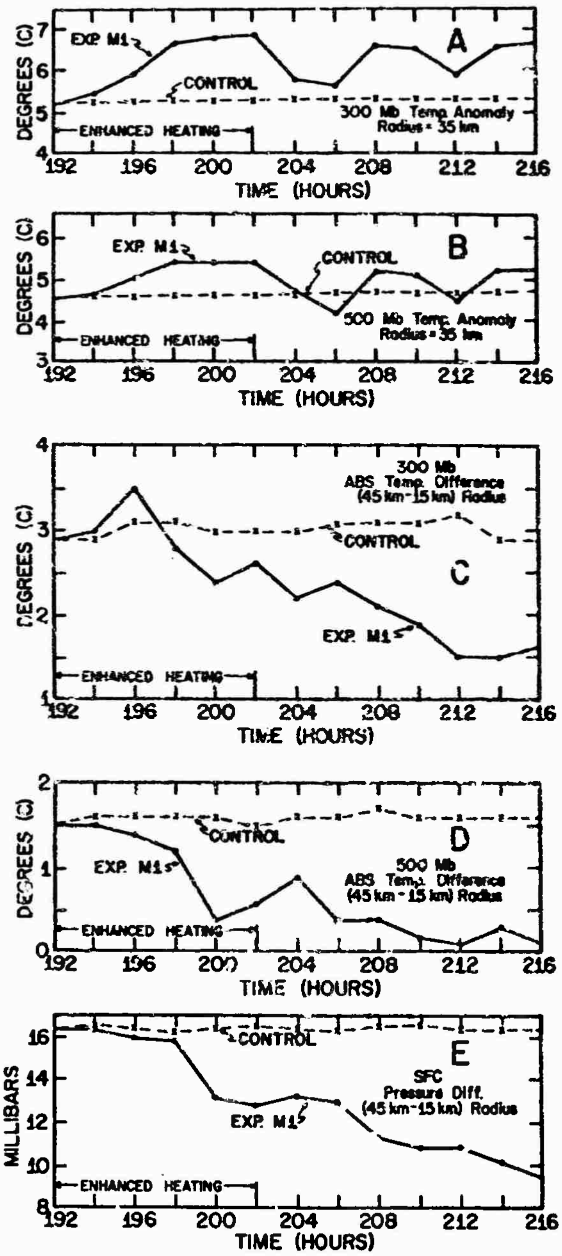

Figure C-14. Comparisons of time histories of Experiment M1 with those of the control: (A) 300-mb temperature anomaly at a radius of 35 km, (B) 500-mb temperature anomaly at a radius of 35 km, (C) temperature differences at 300 mb between radii of 45 and 15 km, (D) temperature differences at 500 mb between radii of 45 and 15 km, and (E) surface pressure differences between radii of 45 and 15 km.

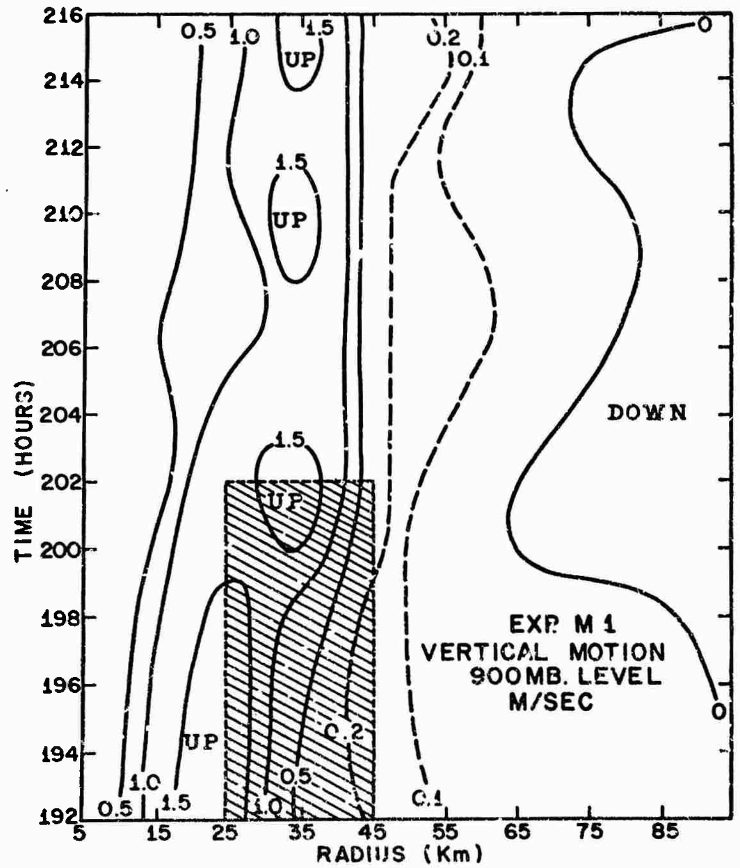

Figure C-15. Results from Experiment M1. Time-radius cross section of 900-mb vertical motion.

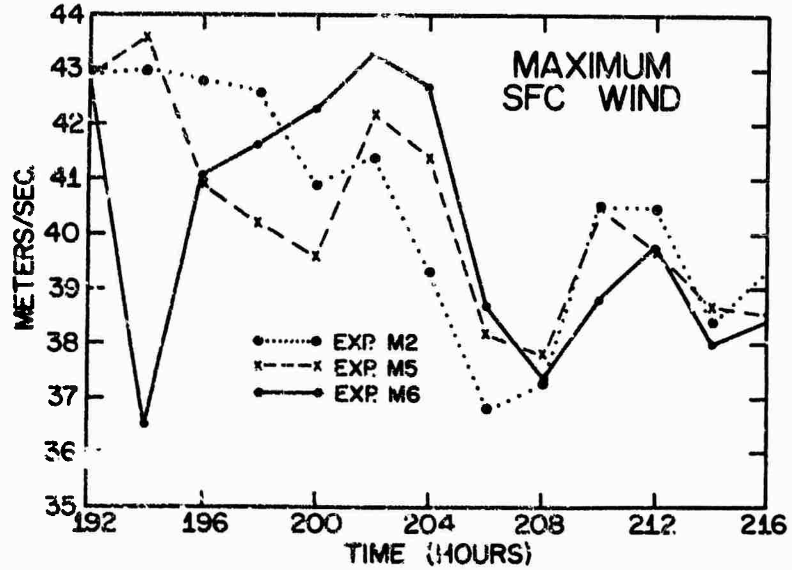

Figure C-16. Time histories of the surface wind maxima for Experiment M2 (dotted), Experiment M5 (dashed), and Experiment M6 (solid).

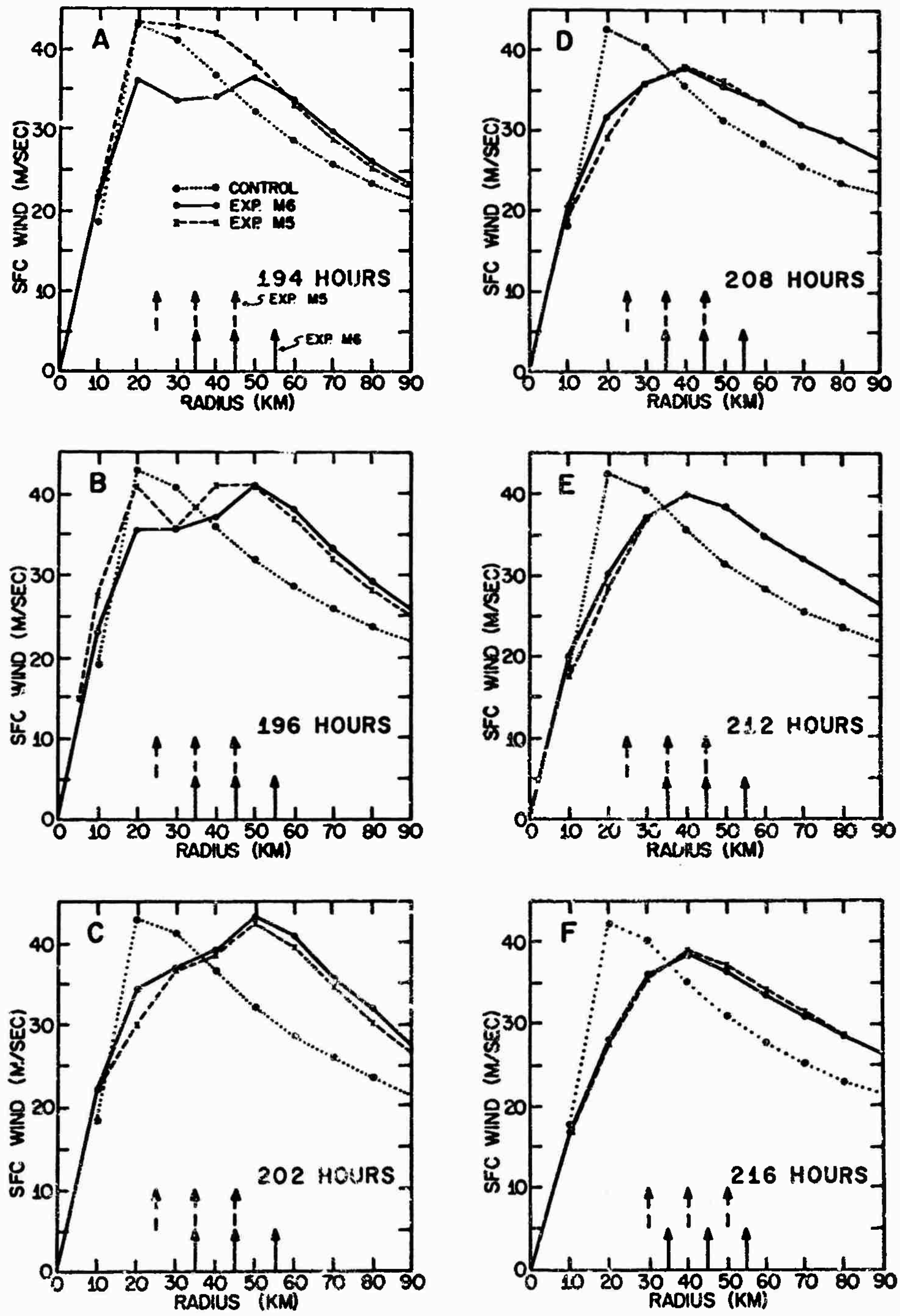

Figure C-17. Comparisons of surface wind profiles for Experiment M5 (dashed), M6 (solid), and the control (dotted), as a function of time. Arrows indicate grid points at which enhanced heating was applied.

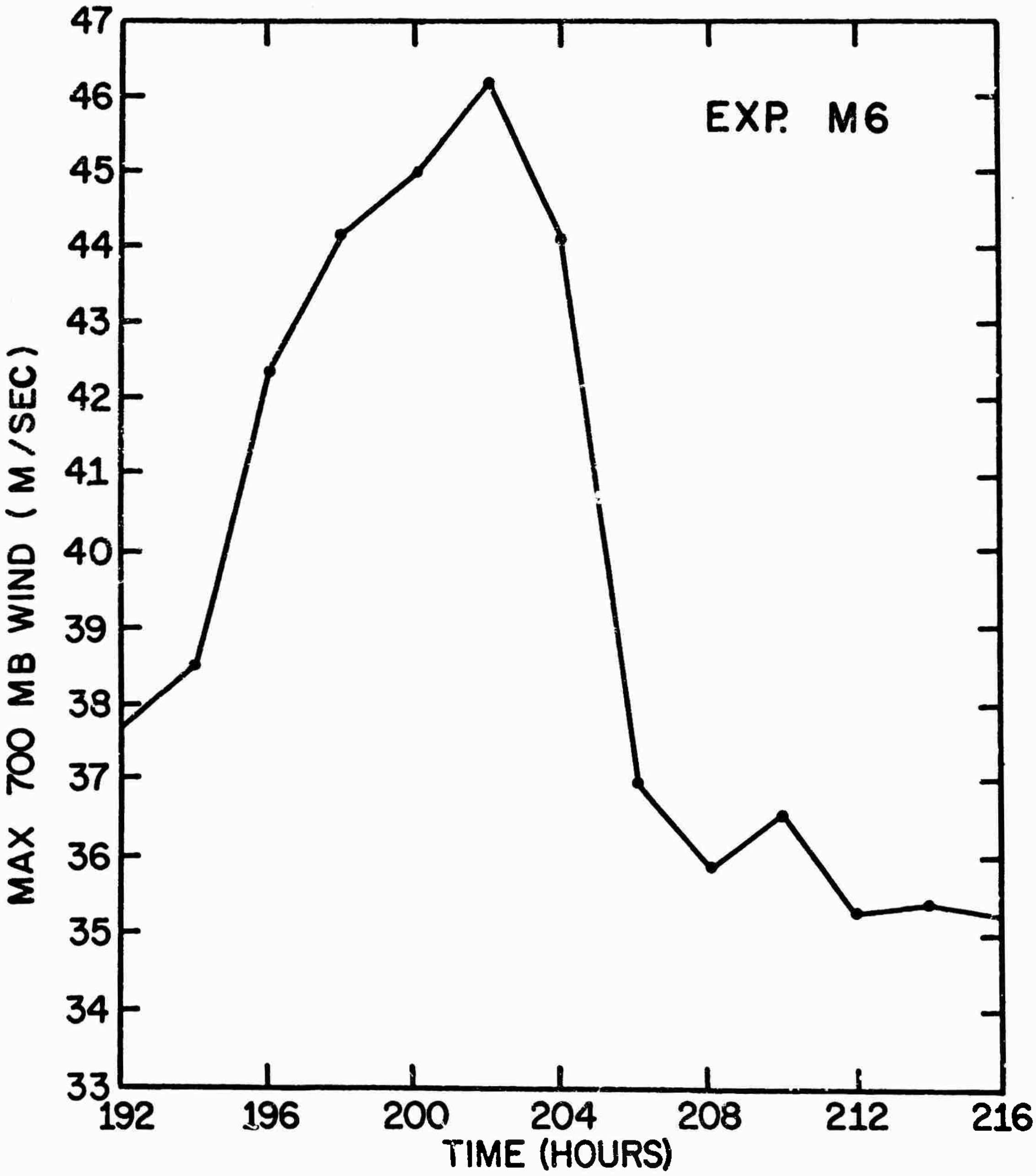

Figure C-18. Time history of the 700-mb wind maxima for Experiment M6.

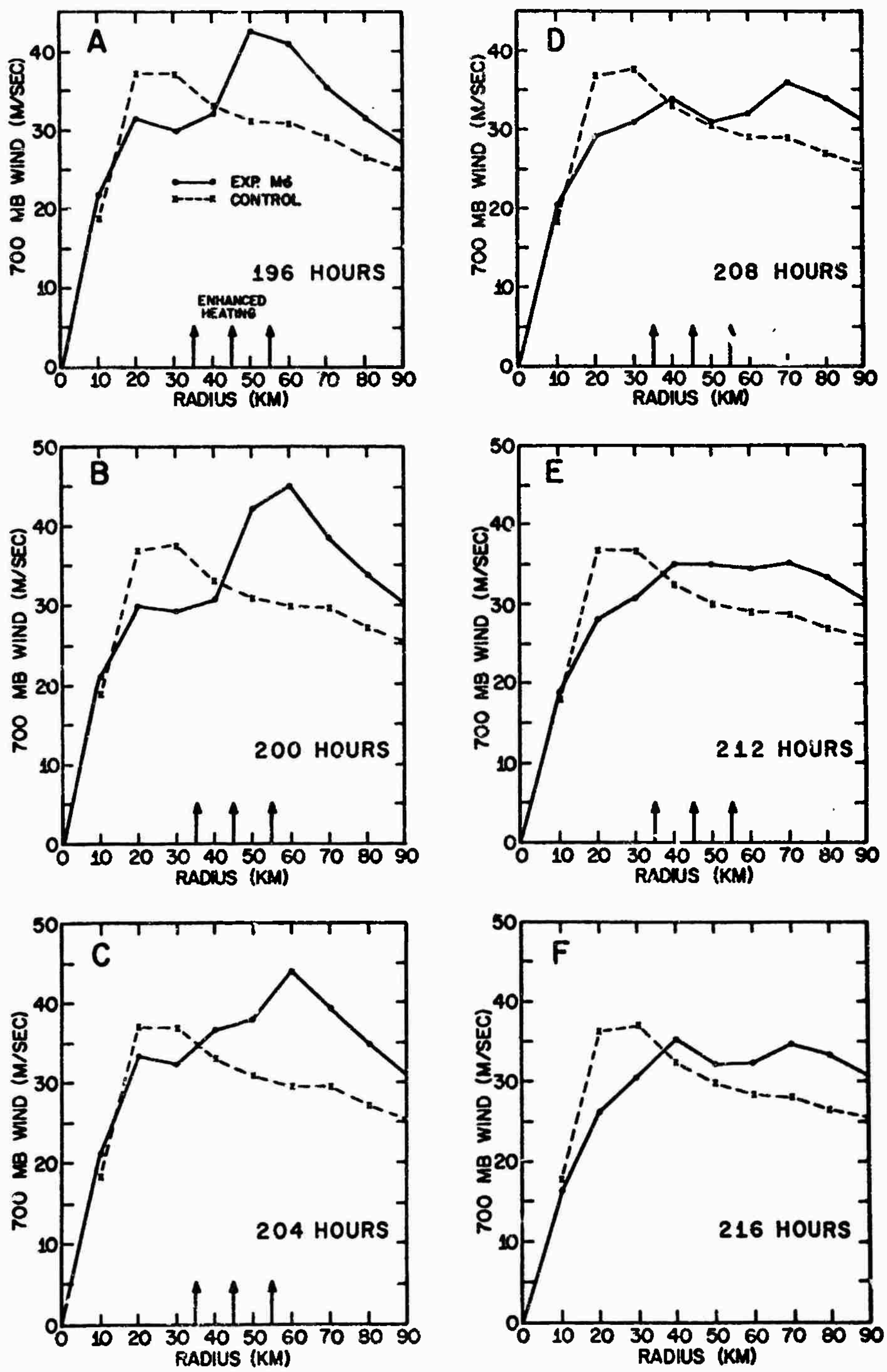

Figure C-19. Comparisons of 700-mb wind profiles for Experiment M6 (dashed) and the control experiment (solid) as a function of time.

become well established. However, by 202 hours, when the enhanced heating is terminated, and thereafter, Experiments M5 and M6 provide results that are much the same (figs. C-17C through F). Beyond 208 hours, the differences between M5, M6, and M1 are all relatively minor (compare figs. C-11 and 17).

The 700-mb winds obtained from Experiment M6 (figs. C-18 and 19) show the original maximum to be destroyed rapidly and to be replaced by a new maximum at a larger radius within the first 4 hours of the enhanced heating. The latter quickly intensifies and continues to intensify until the enhanced heating is terminated at 202 hours. Thereafter, it weakens rapidly. By 212 hours, a new and fairly stable configuration is reached (figs. C-19E and F).

The behavior of the central pressure in Experiment M6 (fig. C-20) is no more dramatic than that found for the experiments discussed previously.

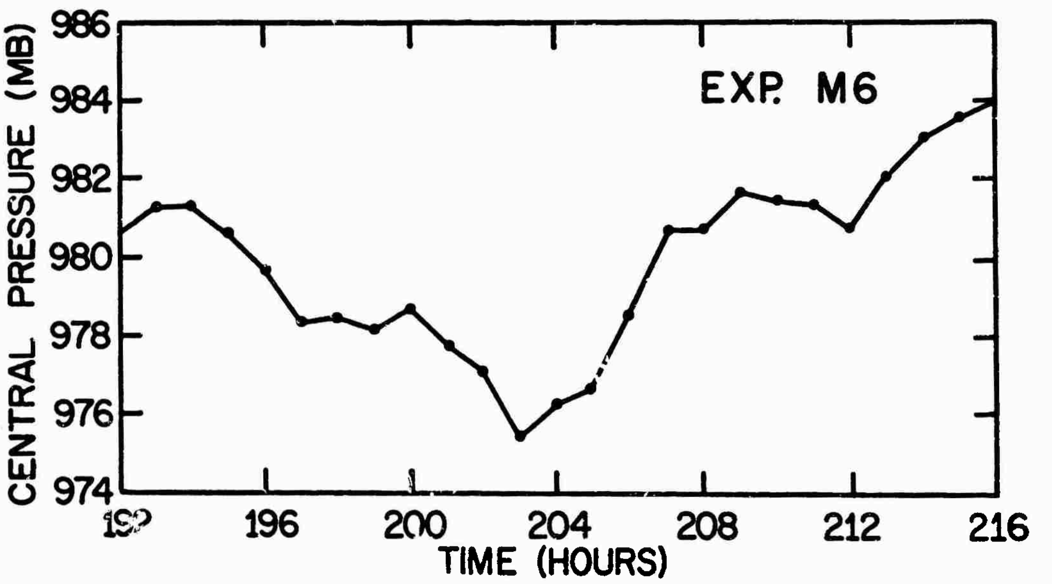

Figure C-20. Time history of the central pressure for Experiment M6.

Figure C-21 compares experiments with normal, large, and extreme heating. In each case, enhanced heating is continuous and at large radii. Before 204 hours, the large heating calculation shows itself to be a transition between the normal and extreme cases. After this time, the solutions in all experiments tend to oscillate and no clear-cut relationship between heating rate and response is apparent. By 216 hours

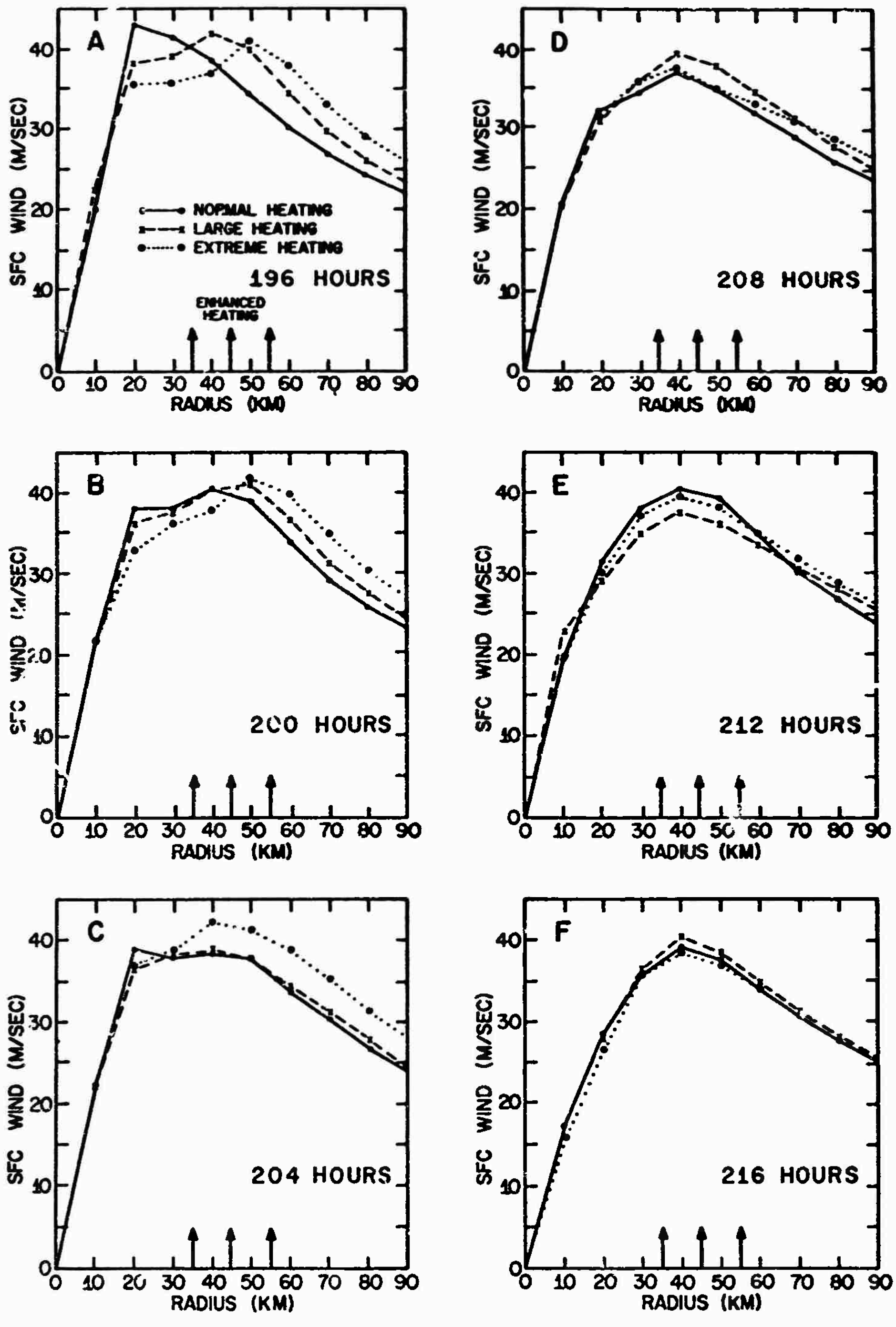

Figure C-21. Comparisons of surface wind profiles for normal (solid), large (dashed), and extreme (dotted), continuous heating at large radii. Arrows indicate the grid points at which enhanced heating was applied.

(fig. C-21D), differences between the three experiments have virtually disappeared.

INTENSIFICATION OF THE SURFACE WIND MAXIMUM THROUGH ENHANCED HEATING

In the introduction, it was suggested that enhanced heating at radii smaller than that of the surface wind maximum should tend to intensify the storm. The experiment (M7) discussed here contains continuous extreme enhanced heating at radii of 15 and 25 km. If the arguments in the introduction are valid (compare figs. C-7 and 8), this should strengthen the surface wind maximum. Figures C-22 and 23 show the deviations from the control to be in the sense anticipated but surprisingly small. Recovery to a state near the control is rather rapid when "seeding" is terminated at 202 hours. At 208 hours, on the scale used for plotting figures C-22 and 23, the experiment cannot be determined from the control.

The 700-mb winds and the surface central pressures (fig. C-24) show a direct response to the "seeding." However, the departure of wind maxima from the control is never more than 2.5 to 3 m/sec. At 700 mb, the increase in the wind maximum is less than the temporary increases found for the cases of "unfavorable" heating. Detailed examination of the response of Experiment M7 is fairly interesting, but will be presented in a scientific paper to be published at a later date.

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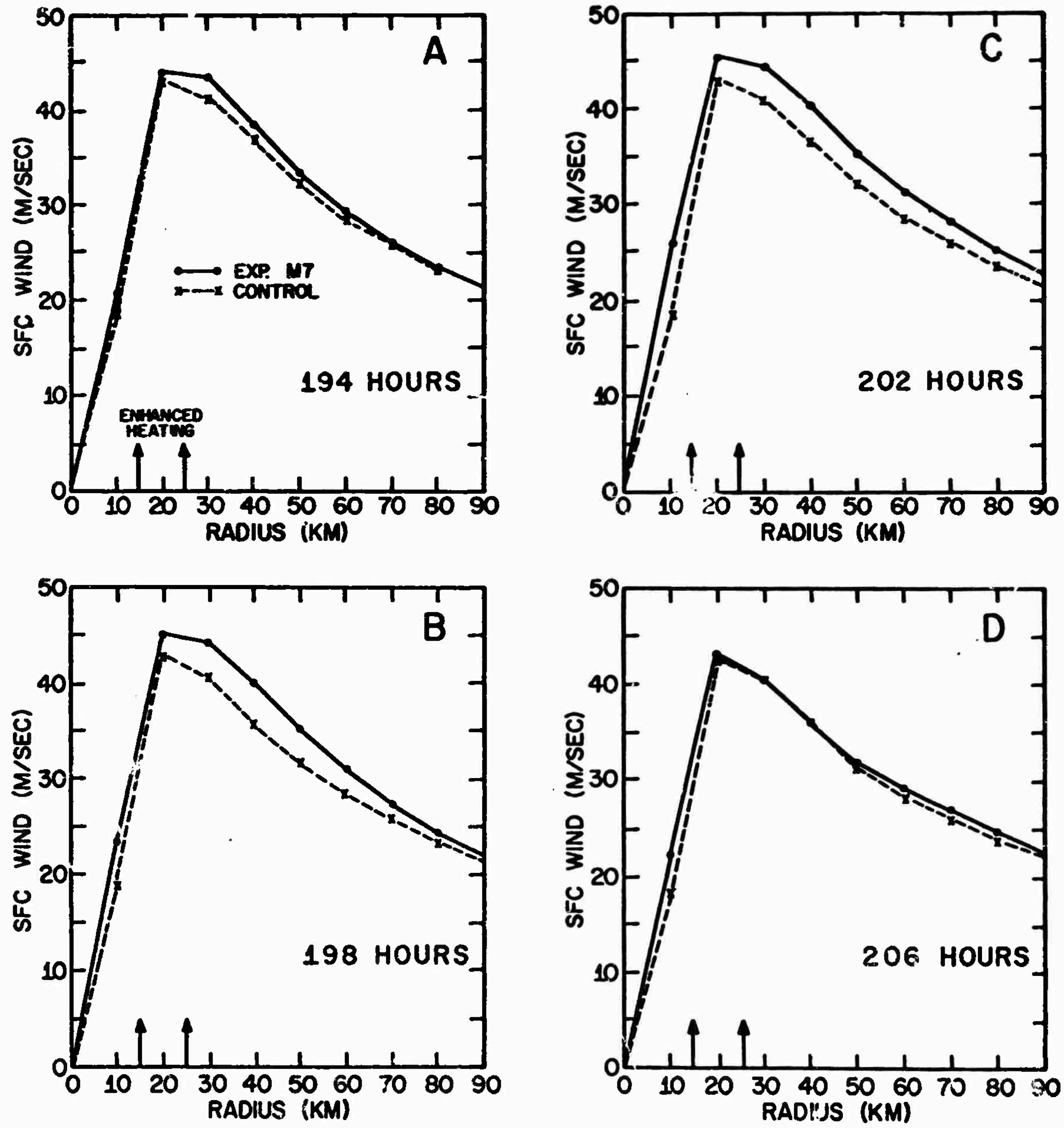

Figure C-22. *Comparison of surface wind profiles for Experiment M7 (solid), and the control experiment (dashed), as a function of time. Arrows indicate grid points at which enhanced heating was applied.*

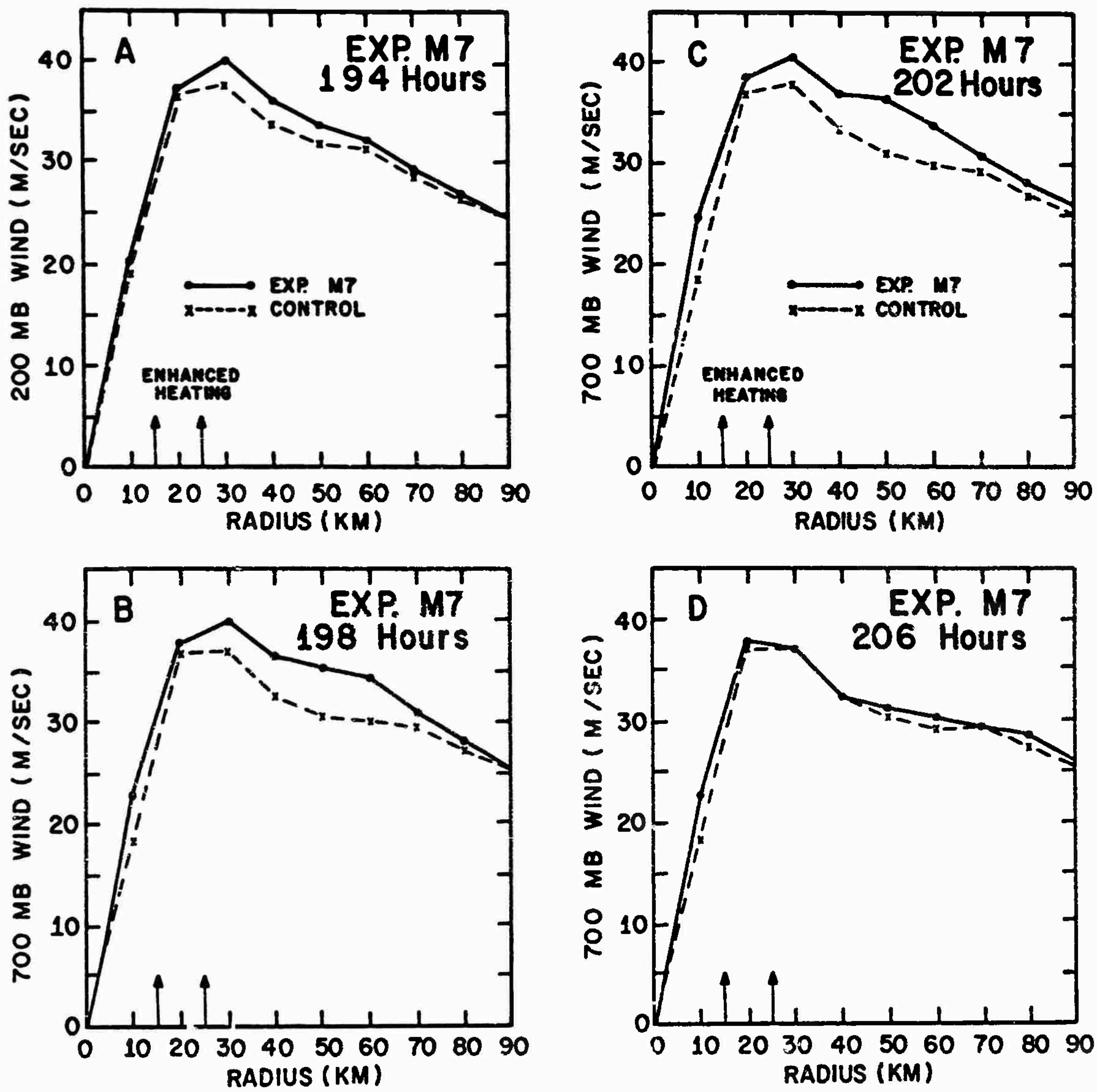

Figure C-23. Comparison of 700-mb wind profiles for Experiment M7 (solid) and the control experiment (dashed) as a function of time. Arrows indicate grid points at which enhanced heating was applied.

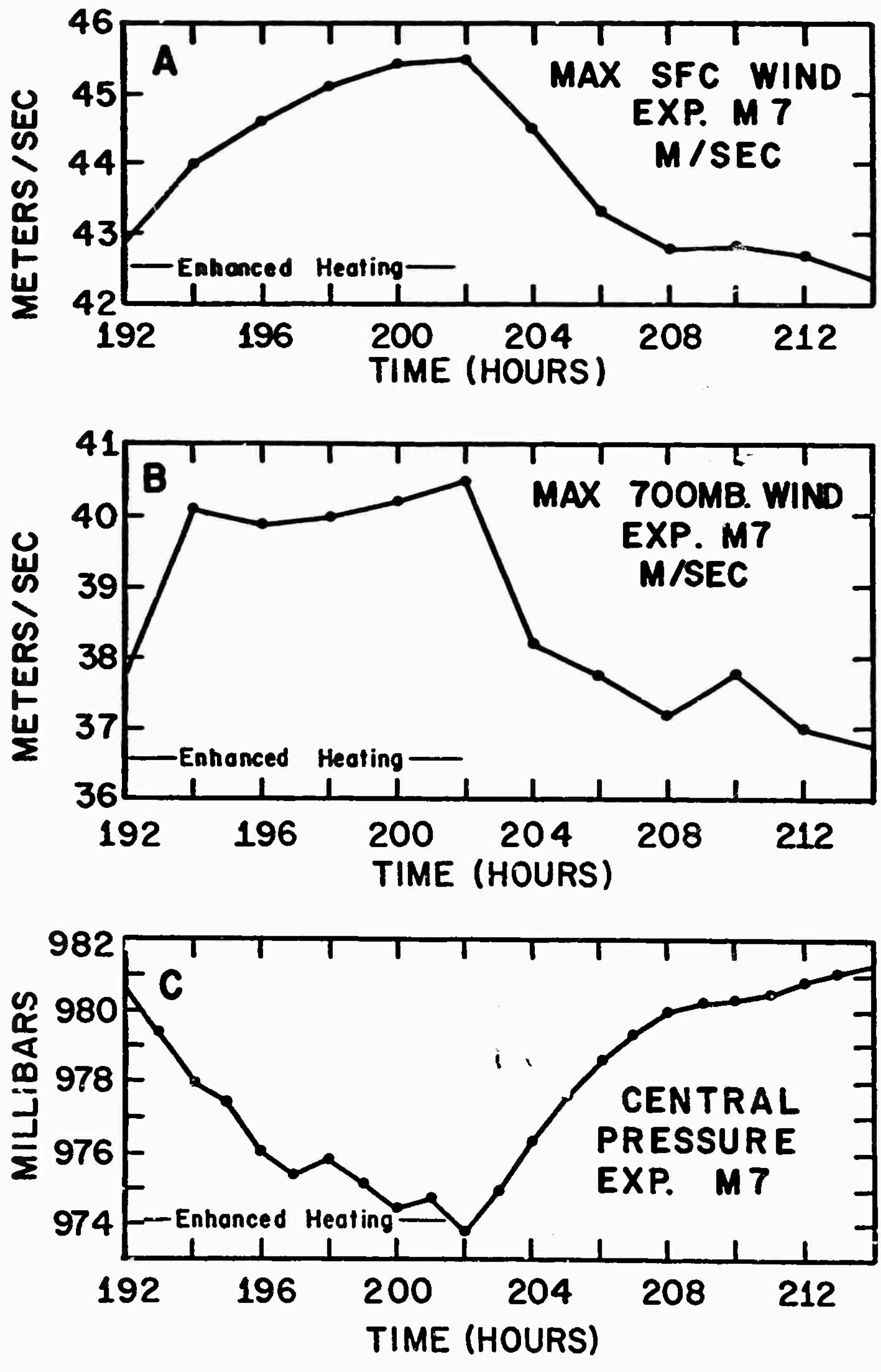

Figure C-24. Results from Experiment M7. Time histories of: (A) maximum surface wind, (B) maximum 700-mb wind, and (C) central pressure.

APPENDIX D

STORMFURY SEEDING PYROTECHNICS

1969

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As described in the STORMFURY Annual Report-1968,[1] the primary seeding unit for the STORMFURY 1969 season was the STORMFURY I, whose characteristics are summarized in table D-1(a). After check firing at NWC, 2,340 STORMFURY I units from 1968 production were available for the 1969 season. To make up the stipulated quantity of 4,000 rounds, an additional 1,000 rounds of STORMFURY I were manufactured in early July 1969, and 660 of the hybrid STORMFURY II units (table D-1(b)) manufactured for the 1968 season were drawn from stock as a reserve. These 4,000 units were received at NAS, Jacksonville, on 23 July 1969, well in advance of the dry-run exercises that opened the 1969 season.

The dry runs provided an opportunity both to familiarize the VA 176 crews with firing and to test the STORMFURY I (1969) rounds (which had been shipped directly from the manufacturer without verification firing at NWC). Satisfactory performance was indicated; only two misfires occurred among 60 rounds flown on two days (29 and 31 July). The remaining 3,940 rounds were subsequently shipped to NAVSTA Roosevelt Roads in two lots, one before and one during the Hurricane Debbie operations.

Five seeding missions were flown on each of the two Hurricane Debbie eyewall operations (18 and 20 August); each A6 was loaded with 208 STORMFURY I units, for a total of 2,080 rounds. Of these, 1,697 were produced in 1968 and 383 in 1969. An additional 17 units (all 1968) were rejected during pre-loading inspection for loose wads, dented cases, etc. On the first day, 64 rounds were returned as misfires; on the second day, 62, giving a misfire rate of 6.1% of the total rounds flown. These data are presented in somewhat greater detail in table D-2.

From the distribution of misfires in the firing racks, it was evident that most were due to "skips" in the firing sequence system. This was borne out by subsequent inspection

[1] The Project STORMFURY Annual Report - 1968, NHRL, ESSA, May 1969, pp. B-1 to B-4.

Table D-1. *Characteristics of STORMFURY Seeding Pyrotechnics (1968 - 1969).*

	(a) STORMFURY I	(b) STORMFURY II	(c) STORMFURY III
Cartridge case	M112 photoflash type	M112 photoflash type	M112 photoflash type
Primer	M59 electric	M59 electric	M59 electric
Fired from	9-A & A-6 ejector rack	9-A & A-6 ejector rack	9-A & A-6 ejector rack
Seeding mixture	LW-83	TB-2/EW-20	EW-20
Charge weight	290 g	225 g	110 g
AgI output (wt.)	190 g	49 g	25 g
Design release alt.	33-35,000 ft	33-35,000 ft	18-20,000 ft
Burn distance (free fall)	18-20,000 ft	15-23,000 ft	2,500 ft
Burn duration	100-120 sec	100-160 sec	25-30 sec

of the misfired rounds at NWC, virtually all of which proved to have functional, unfired primers.

Nighttime firings of STORMFURY I-type units over the NWC ranges indicate that less than 2 percent of those rounds that are ejected fail to ignite and burn properly over the full length of fall. Since this is comparable with the variation in $AgIO_3$ content of the individual pyrotechnic grains, the nucleant delivery totals indicated in table D-2 may be taken for all practical purposes, as correct.

In preparation for the STORMFURY "cloudline" exercises 9-18 September, a new type of seeding round designated STORMFURY III was fabricated (table D-1(c)). Since the NWC Cessna 401 seeder aircraft were to be operated at only 18,000 - 19,000 feet, instead of the 33,000 feet specified for the A6's in the eyewall experiment, a high-efficiency short-burning pyrotechnic grain was required. This was provided by loading a 2.6-inch long EW-20 grain, perforated with a 1/8-inch hole to induce simultaneous burning from the center and both ends, into the same photoflash cartridge used for STORMFURY I, the remaining interior length of the cartridge being occupied by a light wooden spacer. This arrangement insured that virtually all of the AgI produced by each unit would be released above the zero-degree isotherm in the seeded clouds. Each aircraft carried two 26-station ejector racks, firing downward from beneath each engine nacelle.

Of 299 STORMFURY III units provided, 137 were fired during 10 aircraft missions on 6 operational days; an additional seven rounds were fired on a "down" day for test and photographic purposes. Two misfires occurred, but each was successfully refired on a subsequent flight. Otherwise, all the rounds whose trajectories could be observed appeared to function properly.

The quantities of the various STORMFURY seeding units currently on hand are indicated in table D-3. Of these the short-burning STORMFURY III is completely unsuited for hurricane seeding under current operational procedures; the hybrid STORMFURY II was manufactured as a stopgap effort and is substantially less reliable in its performance than the STORMFURY I and differs in its seeding properties. There remains a sufficient number of the latter for one eyewall or several rainband seeding experiments, but not enough to repeat the two days' seeding performed in Hurricane Debbie. The STORMFURY I pyrotechnic device is moreover, classed as strictly experimental; it must be loaded under the supervision of a NWC ordnance technician, and the lack of specific safety devices

Table D-2. Hurricane Debbie seeding data.

Date	Flight	Rounds Loaded	Rounds Fired	Rounds Misfired	AgI Released (kg)
18 Aug	L	208	195	13	37.05
"	M	208	205	3	38.95
"	N	208	194	14	36.86
"	O	208	182	26	34.58
"	P	208	200	8	38.00
Totals	5	1040	976	64	185.44

Date	Flight	Rounds Loaded	Rounds Fired	Rounds Misfired	AgI Released (Kg)
20 Aug	L	208	201	7	38.19
"	M	208	197	11	37.43
"	N	208	190	18	36.10
"	O	208	197	11	37.43
"	P	208	193	15	36.67
Totals	5	1040	978	62	185.82

* Based on nominal 190 gms AgI per unit

Table D-3. STORMFURY Pyrotechnic Inventory (NWC 31 March 1970).

STORMFURY I	(1968)	749)	
		)	1345
STORMFURY I	(1969)	596)	
STORMFURY II	(1968)	660	
STORMFURY III	(1969)	335	

precludes its being used from flush-mounted seeding racks of the type used aboard the P3. The plan is therefore to replace the STORMFURY I with a new unit now being developed by the Navy under the provisional designation WMU-2(XCL-1)/B. This unit is fired from the same type of rack and cartridge case as the previous round, and its pyrotechnic grain is similar in composition and performance, but it incorporates pressure-relief, bore-safety, and time-delay functions that will allow it to be certified for general use in all appropriate racks and aircraft without special supervision. Procurement of 4,000 rounds for the STORMFURY 1970 season is underway.

If exercises of the "cloudline" type are undertaken in 1970, NWC can provide a replacement for the STORMFURY III rounds in the form of the EX 1 MOD 0. This unit, which preceded the WMU-2 in development, has comparable safety features and is loaded with a short EW-20 grain similar to that employed in STORMFURY III. EX 1 MOD 0 has been used successfully from P3A aircraft, and moderate quantities are in stock at NWC.

APPENDIX E

EYE-SIZE CHANGES IN HURRICANE DEBBIE ON 18 AND 20 AUGUST 1969

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Based on the STORMFURY hypothesis that seeding of the hurricane eyewall region will cause changes in storm structure, a study was conceived to observe the experimental area with many airborne radars. It is shown that changes in echo-free area within the eye followed each of the five seedings on 18 August, but followed only one seeding on 20 August. Changes in major axis orientation followed only one seeding on the 18th, but followed each seeding on the 20th. Similar studies conducted recently on unmodified storms suggest that such changes do not usually occur naturally, but they do not exclude this possibility. The repetition of the eye size changes and their timing on the 18th, though they cannot now be explained fully, makes it appear that the seedings were responsible for the variations observed.

INTRODUCTION

This study is an effort to determine if any significant changes occurred in the size and shape of the eye of Hurricane Debbie during the multiple seeding experiments of 18 August and 20 August 1969. The hurricane eye structure is only one of several parameters being studied by radar photography for evidence of a change in the hurricane that might be caused by seeding. It is however, a most significant one. The basic STORMFURY hypothesis, first advanced by Simpson et al. (1963),

modified by Gentry (1969) and recently modelled theoretically by Rosenthal (1970; see app. C) is outlined in other sections of this annual report. It is sufficient to say here only that the hypothesis suggests that a displacement outward of the region of maximum winds might be attributable to seeding. It is thought that an indication of such a displacement of the maximum winds would be found in the outward displacement of the hurricane eyewall as manifested by the precipitation echoes on airborne radar. Hence, this study was conceived to determine if changes in the eye size or shape could be detected following seeding that would indicate whether or not a modification of the storm structure did indeed occur.

INTERPRETATION OF THE DATA

The radar photographs obtained on 18 and 20 August were somewhat less than optimum in quality. Also, the eyewall did not always consist of a closed ring of echoes, but was often broken into segments, especially on the 18th. This made it difficult in many instances to define the eye region and measure its area with a high degree of accuracy. For this reason two methods of measuring the echo-free eye area were used. One consisted of planimetering the echo-free eye region. The other method consisted of measuring the major and minor axes of the eye and computing its area from the ellipse formula. The two measurements, made independently by different people, did not always agree, partly because of subjective interpretation. Due to a lack of continuity in the sequence of radar photographs, which occurred at times, it was difficult to tell on occasion whether an echo at one time was the same echo at a later time.

Another problem was that sometimes only segments of the eyewall were visible. This made it difficult to planimeter the area. However, a major and minor axis could still be defined in these cases. A good example of this problem can be seen later in figure E-4. In general, when the data were relatively good, the two methods produced consistent results.

EYE STRUCTURE CHANGES ON 18 AUGUST 1969

The basic framework of the experiment as stated in the 1969 STORMFURY Operations Plan (1969) provided for five seedings to take place, one every two hours. This was accomplished on 18 and 20 August, 1969.

The typical eye structure of Hurricane Debbie on 18 and 20 August is shown in figures 1A and 1B. On 18 August it was characterized by a single eyewall, open in the east and southeast quadrant during most of the day. Figure E-2 shows the changes in eye radius, echo-free area, major axis orientation, and eccentricity that occurred just before, during, and immediately after the multiple seedings, which are shown by vertical lines at seeding times. The planimetered area is shown by the dot-dashed line and the computed area is shown by solid line in the figure.

Eye-size changes on the 18th were much more pronounced than on the 20th. Unfortunately, radar data quality was poorer

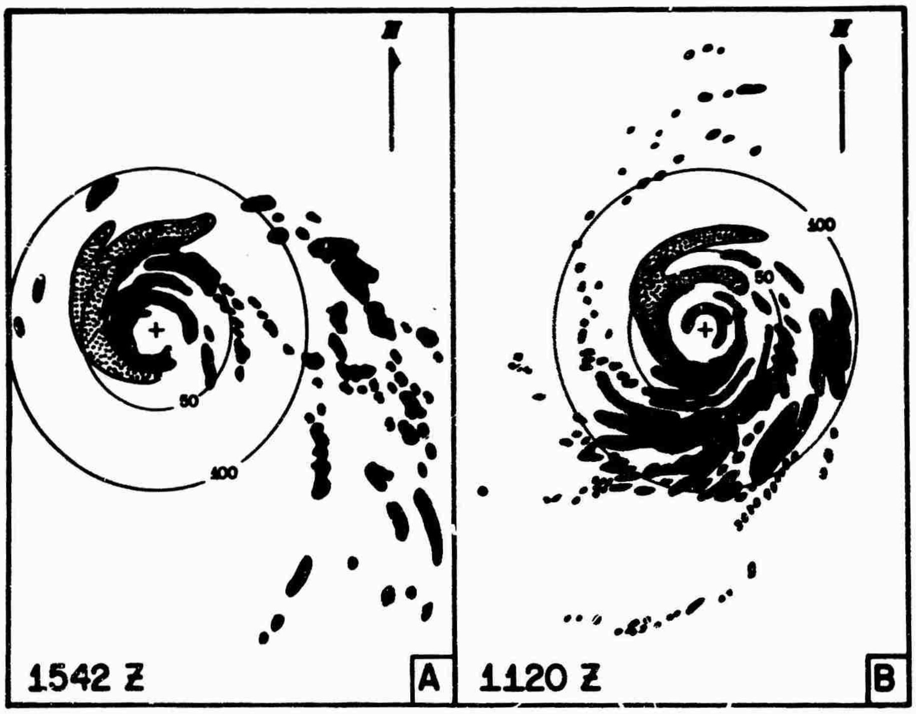

Figure E-1. Typical APS-20 radar composites of Hurricane Debbie on 18 August (A) and 20 August (B).

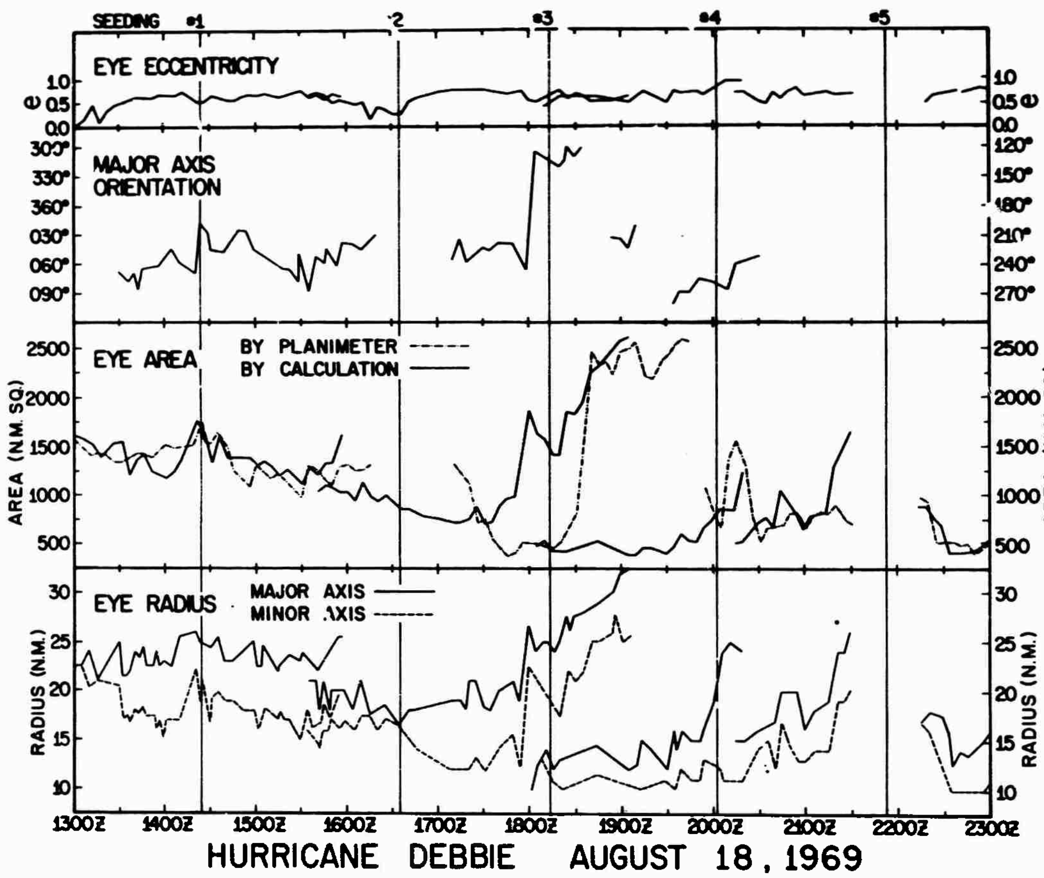

Figure E-2. Eye-configuration changes in Hurricane Debbie from 1100Z to 2100Z on 18 August 1969.

on the 18th, which contributed additional "noise" to the data. The data from 1500Z to 2000Z are considered most reliable since it is an average of measurements from two and sometimes three radars.

Careful study of figure E-2 leads to the following observations. Approximately 1 hour and 15 min after the first seeding, the eye area began to increase rapidly. In 30 min it increased by 50% until it disappeared. Meanwhile, a smaller inner eye had formed, and a double eye structure was visible for about 20 min before the original eye disappeared. Again, approximately 1 hour after the second seeding, there was a rapid increase in the area, which nearly tripled in a period of 15 min. The increase does not appear in the planimetered area because of a difference in interpretation of the radar pictures. Just before

the third seeding, a double eye structure clearly appeared. The larger eye continued to increase in area after this third seeding until it disappeared approximately 1 hour afterward. Meanwhile, the smaller eye slowly increased in area, and shortly after the fourth seeding a sudden increase in area occurred again. A quick reformation of a smaller eye took place, which in turn began a slow increase in area until about 1 hour and 15 min after the fourth seeding, when there was another sudden increase. This time the area doubled in about 10 min. A larger increase may have occurred, but unusable data prevented further measurements until shortly after the fifth seeding. At that time the data showed a smaller eye had formed. No further data were available after 2300Z.

From these measurements, a pattern emerges. It seems more than fortuitous that a rapid increase in eye area should occur approximately 80 min after each seeding. What apparently happened is that, following each seeding, the eyewall expanded outward. As this expansion continued, the eyewall became less well defined and eventually disappeared. A new, smaller eye formed as this process was taking place, and in each case the size of the new eye seemed to be a little smaller than the mean size of the previous one. An example of this process as it occurred following the third seeding is shown in figure E-3.

It should be mentioned at this time that a similar expansion of the radar eyewell was noted by Simpson and Malkus (1964) after the single seeding attempt on Hurricane Beulah during 24 August, 1963. At some time after the seeding, the eye was reported to have increased in radius from about 10 mi to about 20 mi. At that time, it was not certain whether or not this was a natural fluctuation of the storm or a real change caused by seeding.

EYE-SIZE CHANGES ON 20 AUGUST 1969

Eye-size changes on 20 August, shown in figure E-4, were more subtle than on the 18th. The basic eye structure was quite different than on the 18th, being composed of two concentric eyewalls, rather than a single eyewall. The larger eye had a mean radius of 22 n mi, while the smaller one had a mean radius of 12 n mi. Jordan and Schatzle (1961) first reported a similar double eye structure for Donna in 1960. It appears that

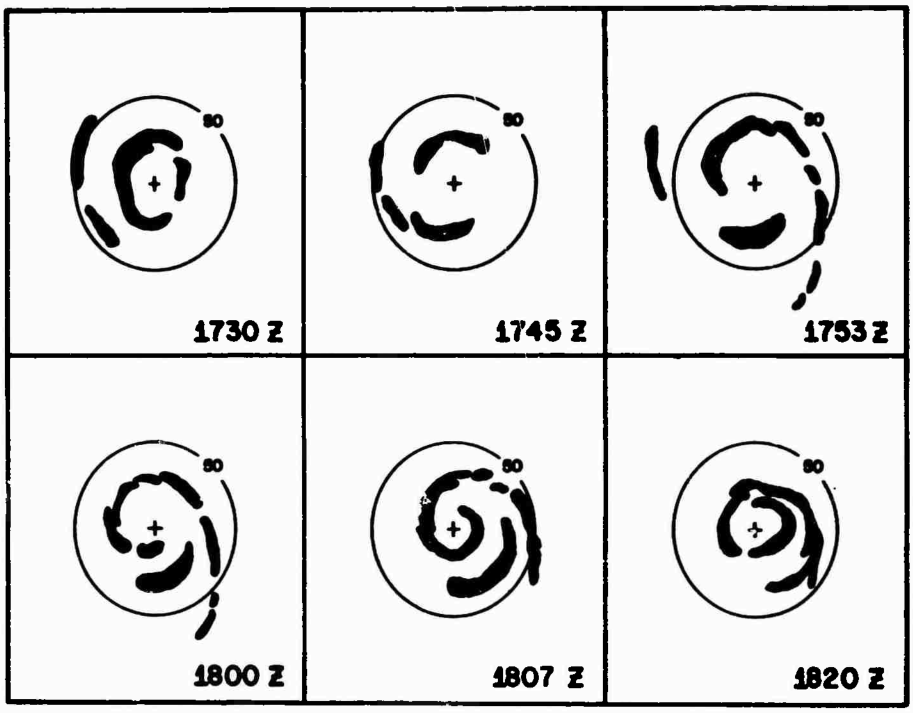

Figure E-3. Process of eyewall expansion as it occurred after the third seeding of Hurricane Debbie on 18 August 1969.

such a storm configuration is not uncommon, as it has been observed in many hurricanes and typhoons since that time.

The seedings were conducted on the inner eyewall, with the exception of the last seeding, which was done mainly on the outer eyewall. The eccentricity of the two eyes did not change markedly during the day, with the outer eye having a mean value of about 0.4 and the inner eye, being more elliptical, having a mean value of about 0.6.

The major axis orientation was different on the 20th than on the 18th. On the 20th the axis did not remain fixed as it did on the 18th, but rotated. The interesting feature is that as it rotated it went through a definite cycle, which had a period of 2 hours. As can be seen from figure E-4, four of these cycles were observed, one following each seeding. The orientation of the major axis was northwest to southeast at each seeding time. Beginning at each seeding time, it took about 1-1/2 hours for the axis to rotate through 180° and complete one-half of the cycle. Then about 1-1/2 hours after each seeding, the rotation

rate of the major axis accelerated rapidly so that it took only 1/2 hour for it to rotate the remaining 180° and complete the cycle. Within 10 min after each seeding the rotation rate decelerated rapidly, and the next cycle began.

Thus, the picture that emerges is deceleration of the major axis rotation rate immediately after seeding, followed 1 1/2 hours later by rapid acceleration. Since the seeding was done in the north-northeast section of the eyewall, and the major axis was oriented northwest to southeast at seeding times, the seeding took place along the minor axis. Thus it appears that one effect of the seeding was to slow down the rate of rotation of the major axis through the seeded area.

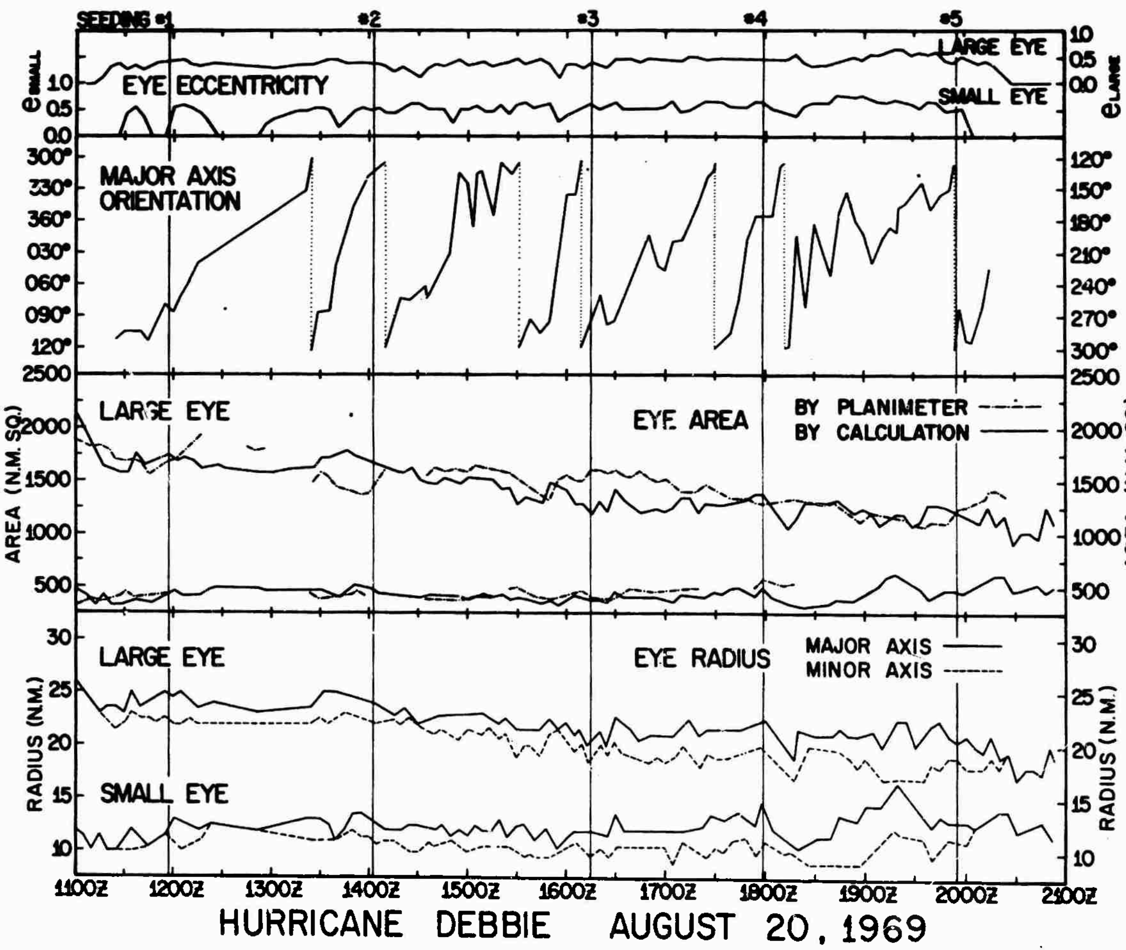

Figure E-4. Eye-configuration changes in Hurricane Debbie from 1300Z to 2300Z on 20 August 1969.

The area and radius of the large and small eyes showed only minor changes, with the following noteworthy features. The area of the large eye showed a general trend to decrease in size during the day. The area of the small eye remained nearly constant until 1900Z, when it began a slight increase, resulting in a much reduced separation between the two eyes by the end of the seeding operation. There was a significant increase in the area of the smaller seeded eye when it increased by 50% about 1 hour and 15 min after the fourth seeding.

EYE-SIZE CHANGES IN UNSEEDED STORMS

The question may be asked whether or not the eye-size changes described above would have occurred if the storm had not been seeded. W. Hoecker and G. Brier (1970, private communication) have conducted a study of the eye-size changes of Hurricanes Carla (1961), Betsy (1965), and Beulah (1967), covering a continuous time period of about 24 hours for each storm. Ground-based radar was used for all three storms, and airborne radar was also used for the Carla study. During the period of study, both Carla and Beulah had a double eye structure, while Betsy had a single eye.

The data sample for Carla was the longest (40 hours). The eye size of this storm showed a trend to decrease from 30 mi in diameter to 23 mi in diameter during the first 24 hours and to remain relatively constant thereafter. Superimposed upon this trend were shorter fluctuations of the order of $\pm$ 4 mi in 4 hours. The Betsy and Beulah eye sizes behaved somewhat similarly.

The data gave no evidence of a cyclic change in eye size or even any sudden individual changes occurring in less than 1 hour. From this limited sample, therefore, it appears that eye-size changes of the type observed in Debbie may be unique. However, further study of unseeded storms is necessary to be more certain of this.

SUMMARY

Airborne radar photographs of Hurricane Debbie, taken on 18 and 20 August, 1969, were used to measure the echo-free area within the eye at 5-min intervals beginning 1 hour before the first seeding and ending 1 hour after the last seeding on both days. Results for the 18th show a sudden increase in echo-free area 1 hour and 15 min after seeding time. Increases ranged from 50% to threefold.

Results for the 20th were quite different. A double eye structure was present on this day, as opposed to the single eye on the 18th. The echo-free area within the smaller eye remained constant throughout the day, and the larger eye slowly decreased in area.

The only evidence of seeding effects on the 20th was observed in the rotation rate of the major axis of the elliptical eye. A slowing of the rate was observed within 10 min of each seeding followed 1-1/2 hours later by a rapid increase in the rotation rate, which continued until the next seeding time. The period of this cycle (the time required for one revolution of the major axis) was about 2 hours.

From these results we arrive at the conclusion that the storm responded in two entirely different ways to seeding on each day. As noted earlier, the storm had quite different structures on the two days. The more conventional single eyewall type storm as encountered on the 18th has been modelled by Rosenthal (1970), and according to his work, seeding must be carried out from the maximum wind region outward in order to have the biggest effect on the storm structure. However, the double eyewall type structure, where there are two wind maxima has not yet been modelled to try to determine where the best place to seed would be. The fact that on the 20th the storm was seeded outside the inner wind maximum, but inside the outer wind maximum, would intuitively lead one to expect different results, which indeed was the case.

Therefore, until more sophisticated model experiments are carried out, it is suggested that if other storms of the double eyewall type are encountered, seeding be carried out on the outer eyewall.

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APPENDIX F

CLOUD PARTICLE SAMPLES AND WATER CONTENTS FROM A 1969 STORMFURY CLOUDLINE CUMULUS

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INTRODUCTION

Navy Weather Research Facility (WEARSCHFAC) personnel operated cloud particle samplers onboard the ESSA-RFF aircraft in 1969 Project STORMFURY operations. The primary objective was to measure the liquid and ice water contents in seeded portions of STORMFURY hurricanes and cloudline cumuli. Technical difficulties prevented useful samples from being obtained on the 18 and 20 August 1969 Hurricane Debbie flights. These difficulties were corrected during the 9 to 19 September 1969 operations, and useful particle samples were obtained in both seeded and nonseeded cloudline cumuli.

This report concerns the WEARSCHFAC cloud particle analysis system and preliminary analyses of water content measurements from particle samples taken during the 15 September 1969 flight south of NAS Roosevelt Roads, Puerto Rico.

CLOUD PARTICLE SAMPLERS

The ESSA-RFF aircraft are equipped with Formvar and foil particle impactors. The Formvar sampler has been described by Sheets (1969) and MacCready and Todd (1964). Cloud particles blast through a small slit and embed in liquid Formvar on rapidly moving 16-mm film. The Formvar hardens shortly after exposure and permanent replicas of the particles are produced. The particle-impregnated film is viewed with a 16-mm stop motion projector equipped with a magnifying lens. The smallest size particle that can be viewed is approximately 2 μ in diameter. The largest water and ice particles viewed are roughly 100 μ in diameter. Most larger particles shatter on impact, leaving spurious replicas.

The foil sampler is similar to the one described by Brown (1961). A strip of aluminum foil moves slowly past a large sampling orifice equipped with a shutter. The shutter exposes the foil for only an instant and prevents particles from landing on one another. The particles leave distinct indentations in

the foil, because it is pressed against a drum with regularly spaced 250-μ striations. Unlike the Formvar samples, fragments from shattered particles do not leave impressions on the foil. The crater-pocked foil strips are photographed and viewed with a 35-mm filmstrip projector (see fig. F-1). Particles larger than 200 μ in diameter can be viewed. Ice and water particles can be differentiated with some uncertainty.

CLOUD PARTICLE ANALYSIS SYSTEM

The 16-mm Formvar and 35-mm foil film strips are projected on the WEARSCHFAC CALMA 302 digitizer. The magnified particle images are digitized onto magnetic tapes, which are processed by the WEARSCHFAC UNIVAC 1107 computer. Particle size and numbers are calculated from the digitized information. Particle number-densities are computed from:

$$N(i) = n(i)/(U\ E\ A),$$

where $N(i)$ is the particle number-density (cm^{-3}) for the i^{th} size interval, $n(i)$ is the particle number for the i^{th} size interval, U is the true air speed ($cm\ sec^{-1}$), E is the exposure time of the foil to the air stream (sec), and A is the exposed foil area from which $n(i)$ was counted (cm^2). The total water content is given by

$$W_T = W_L + W_I + W_U,$$

where W_T is the total water content, W_L is the liquid water content, W_I is the ice water content, and W_U is the unknown water content (particles that cannot be recognized as either ice or water). The liquid, ice, and unknown water contents are determined from

$$W = \sum_{i=1}^{n} \frac{4}{3} \pi\, r(i)^3\, N(i)\, \rho,$$

where W is the particle water content for all size intervals ($g\ cm^{-3}$), $r(i)$ is the particle radius for the i^{th} size interval (cm), and ρ is the particle mass-density ($g\ cm^{-3}$).

At present, the foil data-processing program is operational, and the more complicated Formvar program is being developed.

Cloud particle images from the foil sampler are counted and sized by the digitizer operator according to a modified scheme

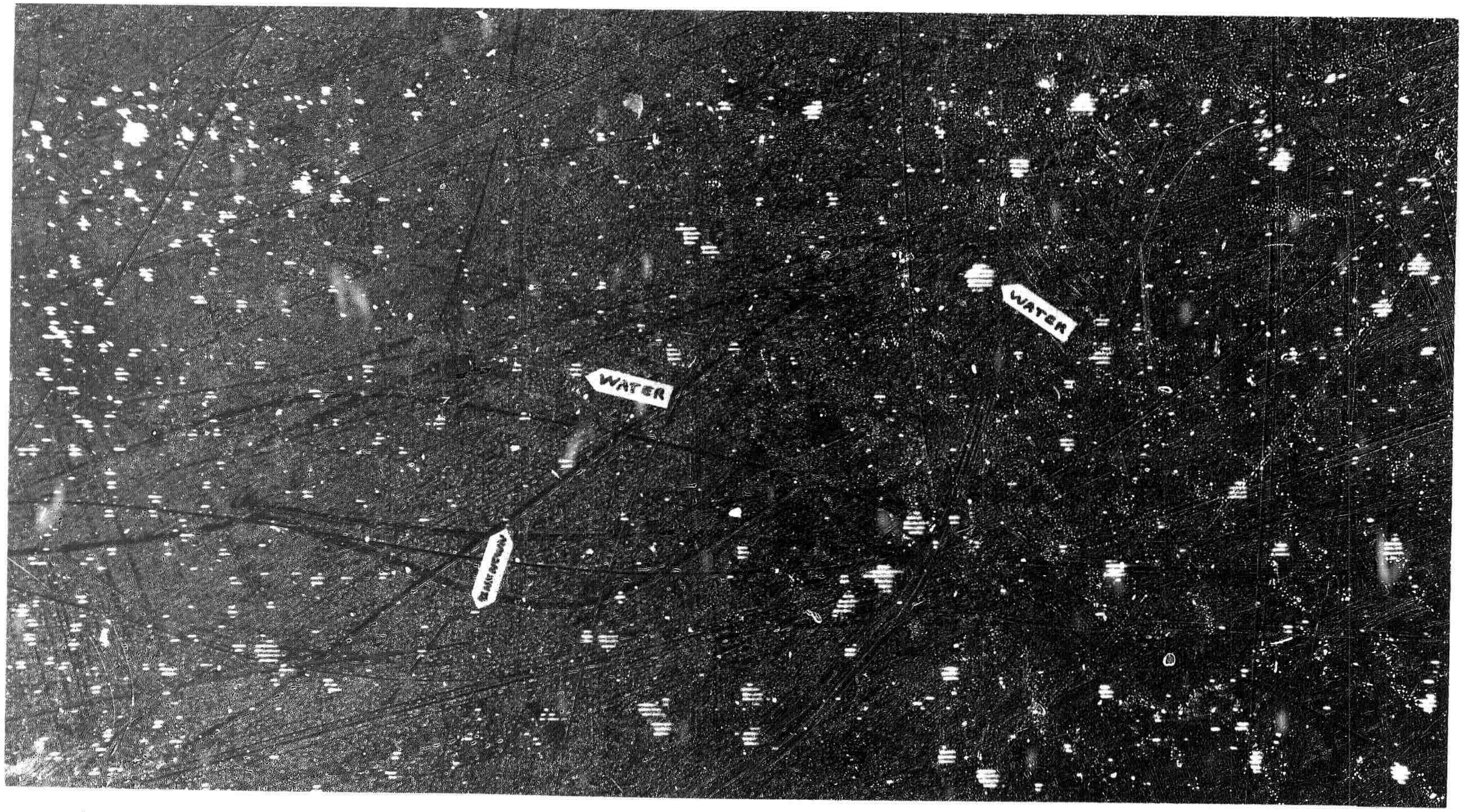

Figure F-1. Typical cloud particle images are shown on a foil strip. Suggested interpretations of a few images are given. The sample was taken at -5 °C on 15 September 1969 in a STORMFURY cloudline cumulus.

originally developed by Takeuchi (1969). Briefly, the foil strip is subdivided into 5-sec segments (see fig. 1). Within each segment, all particles greater than three striations (d $\geq$ 500 μ) in size are traced with the digitizer. Only these particles can be recognized as either ice or water. The one- and two-striation particles are lumped into the unknown water content category. These particles are assumed to be approximately 200 and 300 μ in diameter, respectively. At least 105 of the one- and two-striation particles should be counted in a segment to produce a statistically significant sample.

CLOUD PARTICLE SAMPLES AND WATER CONTENT RESULTS

Preliminary results of the total water-content analysis from one pre-seed penetration of 15 September 1969 STORMFURY "cloudline" cumulus are presented in figures 2 and 3. The remaining pre- and post-seed analysis is underway. The aircraft

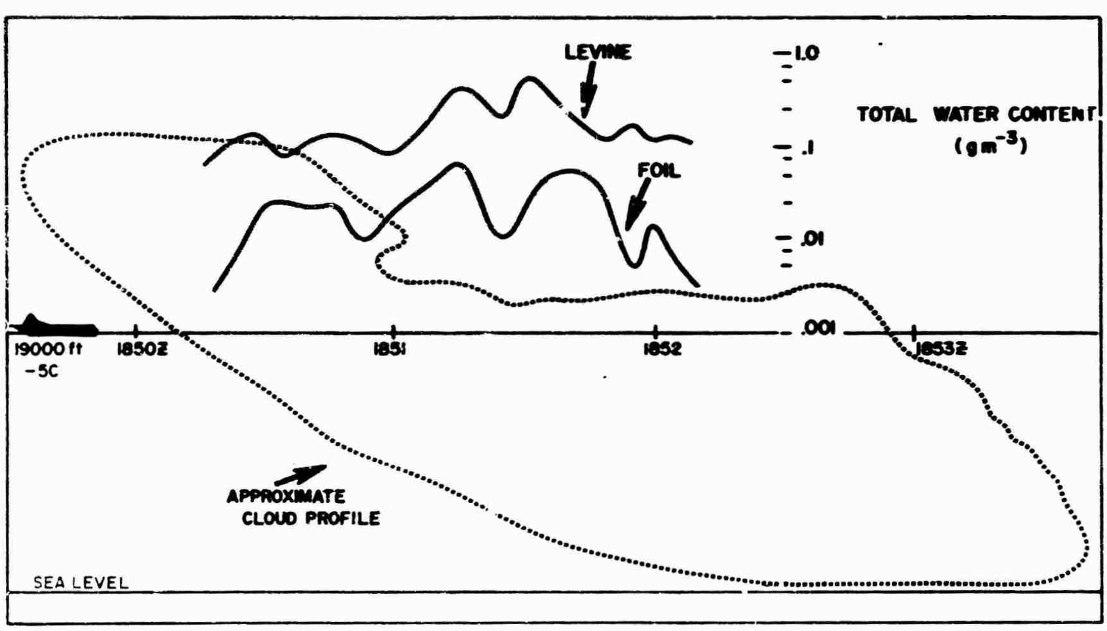

Figure F-2. Comparison of total water contents measured by the Levine instrument and foil cloud particle sampler. The data are from STORMFURY "cloudline" flight B, cloud 1, pass 1, on 15 September 1969.

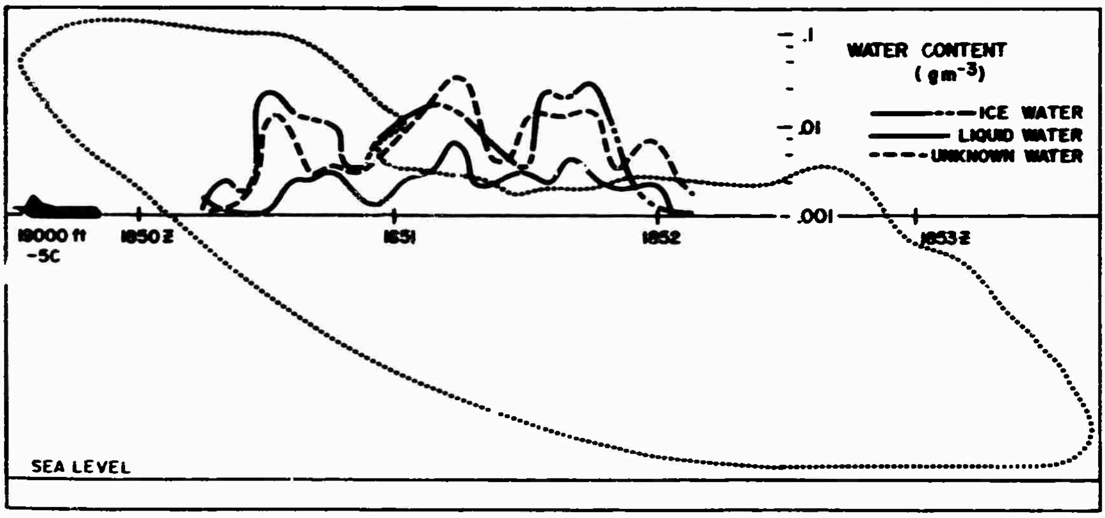

Figure F-3. Components of the total water contents from the foil instrument.

flight data used to construct these figures were provided by ESSA-NHRL.

Figure F-2 shows the periodic trace of the water content from the Levine instrument and the water content measured by the foil sampler. A tenuous agreement is apparent between the peaks and troughs of the two traces. The larger Levine values are probably a result of the fact that the Levine instrument samples particles smaller than the foil sampler was designed to measure. The Formvar instrument was designed to measure these smaller particles. When the analysis of the Formvar samples is complete and the results have been incorporated with the foil values, the resulting water contents should agree more closely with the Levine values.

The components of the total water content from the foil instrument are illustrated in figure F-3. Partitioning the total water content in this manner may aid in identifying the large amounts of ice hypothesised by St. Amand et al. (1970) to be produced by seeding. Takeuchi (1970) and Weinstein and Takeuchi (1970) have tentatively identified artificially produced ice from similar foil and Formvar particle samples taken in seeded Flagstaff cumuli. WEARSCHFAC will make a determined effort to establish the effects of seeding hurricanes and tropical cumuli through its STORMFURY cloud particle sampling program.

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APPENDIX G

PROJECT STORMFURY HURRICANE AND TYPHOON SEEDING ELIGIBILITY

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During the past 2 years, studies were completed to determine opportunities for seeding hurricanes in the Atlantic and Pacific. These studies were published in the Project STORMFURY annual reports of 1967 and 1968, and cover the rules for seeding eligibility adopted in 1967. One of these rules said, "A storm or hurricane is eligible for seeding as long as the forecast states that there is a small probability (10% or less) of the hurricane coming within 50 miles of a populated land area within 24 hours after seeding."

This study of new hurricane areas concerns probable increases in number of storms for experimentation that would result from changing the rules for eligibility for seeding and from lengthening the STORMFURY season. Tracks of hurricanes in the years 1954-69 were checked to determine if the storms would have been eligible for seeding under either of the 1967 rules stated above or possible revisions of that rule that would change the 24-hour limitation to either 18 hours or 12 hours. The study was also expanded to add the months of June, July, and November. As in previous studies, this one includes both hurricanes (Atlantic) and typhoons (Pacific). Table G-1 lists the hurricanes by month and year, area where seeding could have occurred, most likely base of operations, and the type of redefined eligibility for seeding.

The small probability (10% or less) stipulated was also examined to determine if an increase to 25% or 50% would significantly change the number of storms eligible. It appeared that this increase would not be significant, but that a change of the "time after seeding" requirement with its attendant reduction in probability ellipse size would be more effective. In addition, retention of the "10% or less" portion of the rule appears advantageous politically until we really understand the effects of the modification attempts.

Table G-1 shows several interesting things. First, only three, or 8%, of the hurricanes (during the 16 years for which we have forecast data) would have been eligible for seeding, during June, July, and November. Two of these hurricanes occurred in July, one in November, and none in June. One additional hurricane would have been eligible in July if the "time after seeding" portion of the rule had been relaxed. This suggests that benefits of extending the STORMFURY season to the other months may be less than the probable costs and inconvenience of having all of the forces of other programs committed to STORMFURY for a longer period. Having a dry run and cloudline mission in July, however, would be very desirable to help prepare all forces for the earlier August storms.

During the same 16 years, eight additional hurricanes would have become eligible based on the "18 hours after seeding" rule. Of these eight, three were in the Atlantic, three in the Caribbean, and two in the Gulf of Mexico. Three additional opportunities would be added if the rules were further relaxed to the "12 hours after seeding" rule. All of these occurred in the Gulf of Mexico. One of these hurricanes was also eligible while it was in the Caribbean Sea. Even though the increase in opportunities achieved by lowering the time after seeding to 18 hours is rather small, it is worthwhile if it affords an opportunity that would otherwise be lost by rules that are overly restrictive.

Table G-2 lists the hurricanes eligible for seeding under current eligibility rules. This list contains only hurricanes that occurred between 1 August and 30 October.

Table G-3 lists the tropical storms that would have been eligible during the 16 years for which we have data. Fourteen of these storms could be considered as candidates for rainband-type experiments. Of these 14, three were also eligible when they were of hurricane intensity.

From this, one might expect that an average of nearly one opportunity for experimenting on tropical storms per year should occur.

The study of typhoons passing within range of Pacific bases was governed, as during the earlier studies, by the following guidelines:

1. The typhoon must be within 600 miles of the operation bases, Guam or Okinawa.

2. Maximum winds must be at least 65 knots.

Table G-1. Hurricanes Eligible for STORMFURY Experiment.

Year/Month		Name	Ocean	Operating Bases	Ellipse
1954	8	Carol	Atlantic	Jacksonville	24 hr
1954	9	Edna	Atlantic	Jacksonville	18 hr
1954	10	Hazel	Caribbean	Guantanamo Bay	24 hr
1955	8	Connie	Atlantic	Jacksonville/Roosevelt Rds	24 hr
1955	8	Dianne	Atlantic	Jacksonville/Roosevelt Rds	24 hr
1955	8	Edith	Atlantic	Roosevelt Rds	24 hr
1955	9	Flora	Atlantic	Bermuda	24 hr
1955	9	Ione	Atlantic	Roosevelt Rds/Jacksonville	24 hr
1955	9	Janet	Caribbean	Guantanamo Bay	24 hr
1956	8	Betsy	Atlantic	Jacksonville	24 hr
1956	11	Greta	Atlantic	Roosevelt Rds	24 hr
1957	9	Carrie	Atlantic	Roosevelt Rds	24 hr
1958	8	Cleo	Atlantic	Bermuda	24 hr
1958	8	Daisy	Atlantic	Jacksonville	24 hr
1958	9	Fifi	Atlantic	Roosevelt Rds	24 hr
1958	9	Helene	Atlantic	Jacksonville	24 hr
1958	9	Ilsa	Atlantic	Roosevelt Rds	24 hr
1958	10	Janice	Atlantic	Jacksonville	24 hr
1959	7	Cindy	Atlantic	Jacksonville	24 hr
1959	9	Gracie	Atlantic	Jacksonville	24 hr
1959	9	Hannah	Atlantic	Roosevelt Rds	24 hr
1960	7	Abby	Caribbean	Roosevelt Rds	24 hr
1960	8	Cleo	Atlantic	Jacksonville	24 hr
1960	9	Donna	Atlantic	Barbados/Roosevelt Rds	18 hr
1961	7	Anna	Caribbean	Guantanamo Bay	18 hr
1961	[illegible]	Betsy	Atlantic	Bermuda	24 hr
1961	9	Carla	Gulf of Mexico	New Orleans	24 hr
1961	9	Esther	Atlantic	Roosevelt Rds	24 hr
1961	10	Frances	Atlantic	Jacksonville	24 hr
1962	9	Daisy	Atlantic	Roosevelt Rds	24 hr
1962	10	Ella	Atlantic	Jacksonville	24 hr
1963	8	Beulah	Atlantic	Roosevelt Rds	24 hr
1963	9	Flora	Atlantic Caribbean	Roosevelt Rds Roosevelt Rds	24 hr 18 hr
1963	9	Edith	Caribbean	Roosevelt Rds	18 hr
1963	10	Ginny	Atlantic	Jacksonville	24 hr
1964	8	Dora	Atlantic	Roosevelt Rds	24 hr
1964	9	Ethel	Atlantic	Roosevelt Rds	24 hr
1964	9	Gladys	Atlantic	Roosevelt Rds	24 hr
1964	9	Hilda	Gulf of Mexico	Pensacola	18 hr
1964	10	Isbell	Atlantic	Jacksonville	18 hr
1965	[illegible]	Betsy	Atlantic	Roosevelt Rds	24 hr
1965	10	Elena	Atlantic	Roosevelt Rds	24 hr
1966	8	Faith	Atlantic	Jacksonville/Roosevelt Rds	24 hr
1967	9	Beulah	Caribbean Gulf of Mexico	Guantanamo Bay New Orleans	12 hr 12 hr
1969	8	Debbie	Atlantic	Roosevelt Rds	24 hr
1969	8	Camille	Gulf of Mexico	Jacksonville	12 hr
1969	10	Laurie	Gulf of Mexico	Jacksonville	18 hr
1969	10	Inga	Atlantic	Bermuda	24 hr

Table G-2. Annual Frequency of Hurricanes Eligible for Seeding Between 1 August and 31 October Under Forecasting Techniques Criteria approved for STORMFURY Operations Subsequent to 1967.

Year	Atlantic	Gulf of Mexico	Caribbean Sea	Total
1954	1	0	1	2
1955	4	0	1	5
1956	1	0	0	1
1957	1	0	0	1
1958	5	0	0	5
1959	2	0	0	2
1960	1	0	1	2
1961	2	1	0	3
1962	2	0	0	2
1963	3	0	0	3
1964	3	0	0	3
1965	2	0	0	2
1966	1	0	0	1
1967	0	0	0	0
1968	0	0	0	0
1969	2	0	0	2
Total	30	1	3	34

3. The typhoon must be within range for a minimum of 12 daylight hours.

4. The predicted movement of the typhoon must indicate that it will not be within 50 miles of a land mass within 24 hours after seeding.

From 1961 through 1969, during the months of August, September, and October only, 27 typhoons would have been eligible for experiments conducted from Guam and 28 from Okinawa (see table G-4). This gives an average number of 3.0 opportunities per year for operations based from Guam and 3.1 opportunities per year from Okinawa.

Because the 55 eligible typhoons contain 7 that were counted eligible from both Guam and Okinawa, the average number of individually eligible typhoons per 3-month period is 5.3.

Table G-3. Tropical Storms Eligible for Rainband Seeding 1954-1969. (Seeding Time: 0700-1300.)

Year/Month		Name	Ocean	Operating Base
1955	8*	Dianne	Atlantic	Roosevelt Roads
	9*	Ione	Atlantic	Roosevelt Roads
	8	(Unnamed)	Gulf of Mexico	
1956	9	Flossy	Gulf of Mexico	
1957	9	Frieda	Atlantic	Roosevelt Roads
	10	(Unnamed)	Atlantic	Roosevelt Roads
1958	8	Becky	Atlantic	Roosevelt Roads
	9	Ella	Gulf of Mexico	
	9*	Helene	Atlantic	Roosevelt Roads
1959	6	(Unnamed)	Atlantic	Roosevelt Roads
1961	10	Gerda	Atlantic	Jacksonville
1966	7	Celia	Atlantic	Roosevelt Roads
	9	Greta	Atlantic	Roosevelt Roads
1967	10	Heidi	Atlantic	Roosevelt Roads

*Also seedable as hurricane.

Table G-4. Number of Typhoons Meeting Criteria for Seeding Eligibility. Staging Operations From Guam/Okinawa.

	Guam/Okinawa							
Year	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
1961	0/0	0/0	0/3	2/2	2/2	1/0	0/0	5/2
1962	0/0	0/0	1/2	1/1	1/2	i/0	0/0	4/5
1963	0/2	1/1	0/1	0/2	2/2	0/0	1/0	4/8
1964	0/0	2/1	0/0	2/0	0/1	0/0	1/0	5/2
1965	1/0	2/1	1/2	1/2	1/0	1/0	0/0	7/5
1966	0/1	0/0	0/0	3/2	0/0	0/0	0/0	3/3
1967	0/0	0/2	0/0	0/0	2/0	3/1	0/0	5/3
1968	1/2	1/1	1/0	1/2	3/1	2/0	0/0	10/6
1969	0/0	1/0	0/0	1/1	2/0	1/2	0/0	5/3

Since some would be eligible more than once and others could be seeded both from Guam and Okinawa, it is realistic to assume more than six opportunities per 3-month period.

Frequency of eligible typhoons during the months of June and July, although much lower than September and October, are worth noting. On the average, two typhoons per year could be seeded during this 2-month period.

This study yields the following conclusions:

The seeding opportunities for hurricanes are increased by only 8% (three hurricanes during 16 years) if June, July, and November are added to the seeding season. The month of July produced two of the three opportunities. One additional hurricane would have been eligible in July with the slightly relaxed (18 hour) seeding eligibility rules.

The "18 hour after seeding" rule and attendant probability ellipse with requirement for 90% probability of forecast accuracy, adds eight seeding opportunities. The "12 hour after seeding" rule would add only three additional opportunities.

Conducting seeding experiments on typhoons in the Pacific during June and July could be expected to provide an average of two opportunities per year.

APPENDIX H

APPLICATION OF BAYESIAN STATISTICS FOR STORMFURY RESULTS

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INTRODUCTION

The number of hurricane seeding experiments performed to date is quite small and probably will remain so in the near future. This then limits what can be done through classical statistical techniques to calculate the significance of the results. For this reason, various knowledgeable statisticians have suggested that Bayes' equation be used to test the significance of the seeding experiments and to update the probability distributions based on the experimental and model results. An attempt to accomplish this task is described here.

CLIMATOLOGY

The first step was to obtain background information on the fluctuations that occur naturally in a mature hurricane. Various detailed and complicated studies have been made to determine these fluctuations, but for the specific requirements of this study, a rather simple and limited study was made.

Graphs of minimum sea-level pressure versus time were constructed for all tropical cyclones of hurricane strength in the Atlantic, Gulf of Mexico, and Caribbean areas for which data were available at 6-hourly intervals for at least 24 hours for the years of 1961 through 1968.

The maximum wind speeds (defined as the strongest winds present in the storm at the given time) were then computed from the minimum sea-level pressure at 6-hour intervals based on a relationship presented by Holliday (1969). The data presented by Holliday in deriving this relationship showed an average error of less than 5 knots. This results in some uncertainties in the relationship used but probably less than the other uncertainties which result from assumptions made in later computations. The percentage of maximum wind speed changes were then

computed for intervals of 6, 12, 18 and 24 hours. The number of cases ranged from 510 for the 6-hour changes to 429 for the 24-hour changes. The results are shown in figure H-1, where the mean changes ranged from +1.91 to +7.32 percent, reflecting a bias toward deepening storms, and the standard deviations ranged from 7.8 to 18.95 percent for [illegible] and 24-hour changes respectively.

The data are slight[illegible]d because more storms were monitored during the deepening and mature stages than during the weakening stages. Also, some of the storms struck land and dissipated rapidly, and in these cases a dissipating stage comparable to the deepening stage was not recorded.

The 12-hour changes were used as a starting point in this study and for reasons of simplicity the speed changes in the

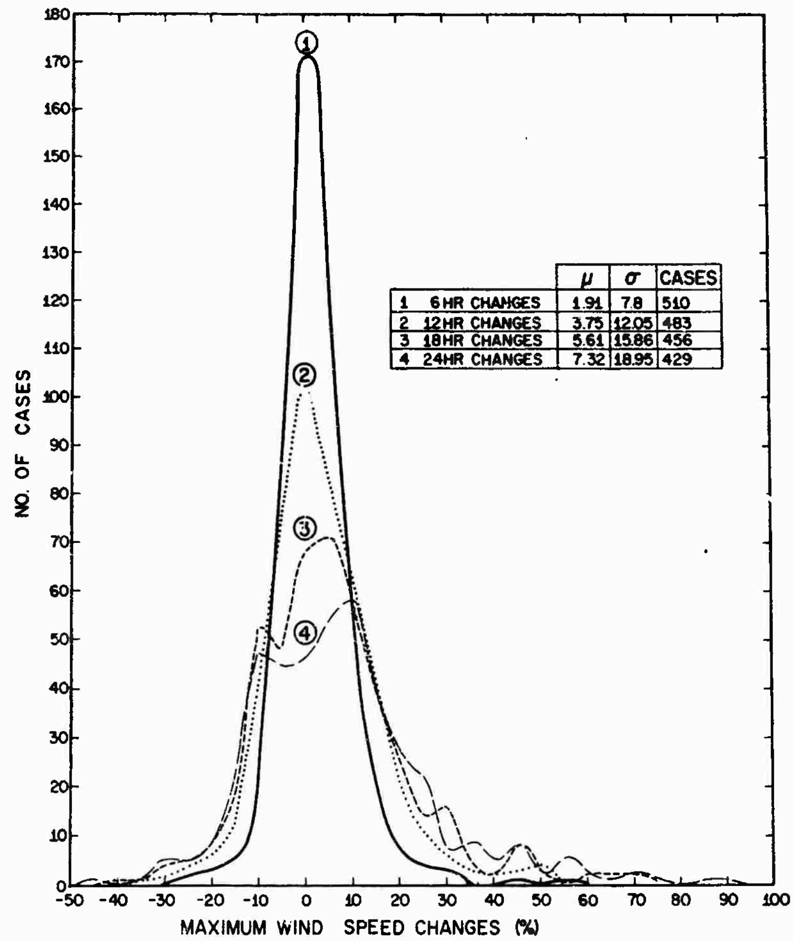

Figure H-1. Maximum wind speed changes for Atlantic hurricanes from 1961 through 1968 for periods of 6, 12, 18, and 24 hours. (Computed from time changes of minimum sea-level pressures.)

calculated maximum winds during the hurricane stage were assumed to follow a normal distribution with a mean of zero and a standard deviation of 12%. This distribution, despite the slight bias in the data, closely approximates that computed for the 12-hour changes and will hereafter be referred to as the climatological distribution.

RESULTS OF EXPERIMENTS

A total of six hurricane eyewall seeding experiments had been attempted by the end of the 1969 hurricane season. The experiments performed on Hurricane Debbie on 18 August and 20 August 1969 were quite different from the other four, which were performed in Hurricanes Esther (1961) and Beulah (1963).

The Hurricane Debbie experiments consisted of five separate seeding periods at 2-hour intervals (Gentry, 1970), while the Esther and Beulah experiments consisted of only one seeding period. There are also some questions about the location of the release of the silver iodide in the Beulah experiment on 23 August 1964 and the Esther experiment on 17 September 1961. About Beulah, Simpson and Malkus (1964) state that "... the silver iodide was dropped in an open almost cloud-free portion and probably could not have entered the tall towers during the 2 1/2 hour monitoring period after seeding." About Esther, Simpson et al. (1963) state that "Apparently all the silver iodide was released .... in the clear air of the eye." In addition to the field experiments mentioned above, a simulated experiment was run with a numerical hurricane model developed by Rosenthal (1970). This experiment was designed to simulate the Debbie seeding experiments and will be referred to as the model experiment in this paper. The Esther and Beulah experiments are mainly used as background information in the calculations that follow since they were quite different from the Debbie experiments. The results of all these experiments are summarized in table H-1.

Each seeding experiment is assumed to be independent for the purpose of the computations made here. This assumption seems quite reasonable since in each case at least 24 hours elapsed between experiments, and in the Hurricane Debbie experiments 38 hours elapsed between seeding operations. A rough calculation based on a mean radial wind component of 10 knots in a layer 1 n mi thick shows that the air located within 60 n mi of the storm center from the surface to 100 mb would be replaced within 18 hours. For a radius of 100 n mi the time required for the complete ventilation would be approximately 30 hours. The assumption of a mean radial wind component

Table H-1. Results of Hurricane Seeding and Model Experiments.

No.	Name	Date	No. of Seedings	Approx Max. Wind Speed Change (percent)
1	Hurr. Beulah	23 Aug '63	1	0*
2	Hurr. Beulah	24 Aug '63	1	-14
3	Hurr. Esther	16 Sep '61	-	-10
4	Hurr. Esther	17 Sep '61	1	0*
5	Hurr. Debbie	18 Aug '69	5	-30
6	Hurr. Debbie	20 Aug '69	5	-15
7	Rosenthal Model	1969	Continuous for 10 hours	-15

*Silver iodide was apparently released in cloud-free regions.

of 10 knots in the lowest 1 n mi layer seems quite reasonable based on previous studies (Malkus and Riehl, 1959; Sheets, 1965). In addition to the long-term ventilation effects, much of the seeding material is expected to be carried upward into the strong outflow region in a very short time and other portions of the agent will be "rained out." In the Debbie experiments, the storm on 20 August seemed to have recovered from the seeding effects that occurred on 18 August,as the maximum wind speeds had again increased to over 100 knots by the time of the second day of seeding.

HYPOTHESIS TESTING

The basic question regarding the success or failure of the seeding experiments is: Did the seeding cause the changes observed in the seeded storms? An attempt is made to answer this question below through hypothesis testing and the use of the evidence form of Bayes' equation.

If we assume that the hurricane seeding experiment represents a problem in sequential testing, we can use Bayes' equation in the evidence form given by (Tribus, 1969, p. 84):

$$ev(H_1|E_n C) = ev(H_1|C) + 10 \log_{10} \frac{P(E_n|H_1 C)}{P(E_n|H_2 C)} \qquad (H-1)$$

where

H_1 is a given hypothesis,

H_2 is all other possible hypotheses,

C is background climatological information,

E_n is the sequence of outcomes on the nth test,

$ev(H_1|E_n C)$ is the evidence in favor of H_1 given the truth of E_n and C,

$ev(H_1|C)$ is prior evidence in favor of H_1 given the truth of C,

$P(E_n|H_1 C)$ is the probability that the sequence E_n would be observed if H_1 and C were true,

and

$P(E_n|H_2 C)$ is the probability that the sequence E_n would occur if H_2 and C were true.

In the computations that follow, we will assume that there are only two possible hypotheses. This is obviously erroneous, as there are an infinite number of hypotheses that could be advanced, but it does give us an opportunity to compare the two proposed here. Also, these two hypotheses are being proposed after the fact, that is after the experimental results have been documented, and a hypotheses could be chosen that would predict the sequence of outcome exactly. However, we shall restrict ourselves to probability distributions resulting from the seeding experiments that are similar in form to the climatological distribution.

We have indicated earlier that assuming a normal distribution to represent climatology is quite reasonable. If we also assume that the seeding experiment superimposes a constant factor on the climatological distribution, i.e., simply shifts the location of the distribution, an assumption of a normal distribution for representing the seeding effect would be justified. The major argument then arises as to just how much the shift should be. Complete agreement on this will probably never be reached, and even majority agreement may be

difficult to obtain. Therefore, a variety of normal distributions representing the probability densities were investigated, ranging from conservative to liberal estimates of the change expected from a seeding experiment; two are presented in this paper. We are choosing the hypothesis H_1 to be that the wind speed changes observed after a seeding experiment were a result of the seeding that generates some given probability distribution, and H_2 is the hypothesis that the observed changes occurred by chance and can be considered coming from a population represented by the climatological distribution.

For the first two cases, we assume that there is no evidence in favor of either hypothesis and that both are equally probable before application of the experimental results. Since no evidence is assumed in favor of either hypothesis before the experimental results, the term $ev(H_1|C)$ is zero in the first step of each computation.

For the first case, we are choosing the following hypotheses:

H_1 = The observed wind speed change after seeding has a probability distribution described by curve A, figure H-2.

H_2 = The observed wind speed change after seeding occurred by chance and has a probability described by curve C, figure H-2, which represents the climatological distribution.

That is, H_1 is the hypothesis that the wind speed changes observed after each seeding experiment came from a population represented by a normal distribution with a mean and standard deviation of -3 and 12% respectively. This distribution indicates a 60% chance of getting a wind speed reduction and a 40% chance of observing a wind speed increase after each seeding experiment.

The mean value of the climatological distribution (representing H_2) is 0 and the standard deviation is 12 percent. This distribution would indicate a 50-percent chance that the wind speeds of a given storm would decrease during the 12-hour period after seeding and a similar probability for showing an increase.

The value of the observed maximum wind speed change was used to determine the probability that such a change would occur, given the distribution associated with H_1 as compared with the one associated with H_2. The results of the comparison

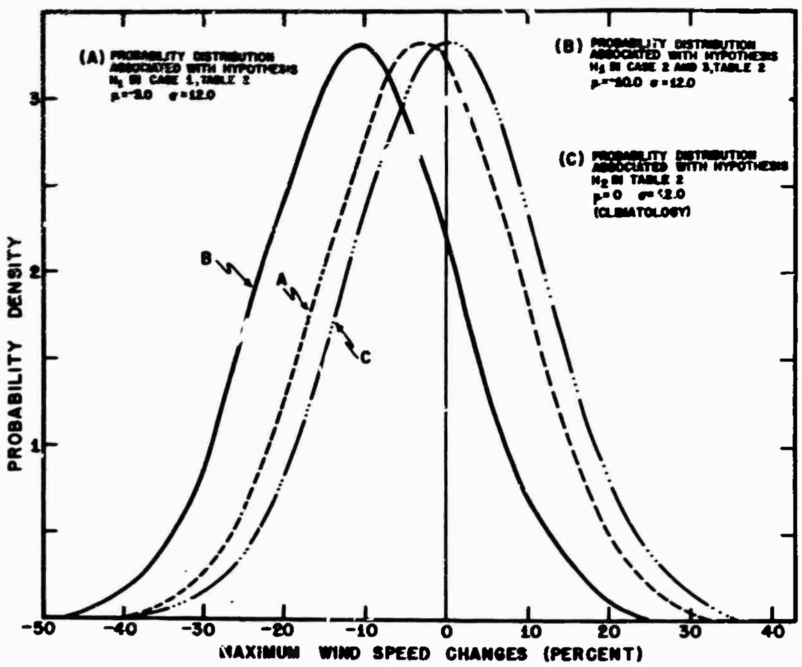

Figure H-2. The probability distribution used in the hypothesis testing listed in table H-2.

of these two hypotheses are listed as case 1 in table H-2. This computation indicates that after the two Debbie seeding experiments, the probability that H_1 is correct compared with H_2 has increased from 50 to 70%.

For the situation listed as case 2 in table H-2, the hypothesis chosen for H_2 is the same as above, but that chosen for H_1 is as follows:

H_1 = The observed wind speed change after seeding has a probability distribution described by curve B, figure H-2.

Curve B is a normal distribution with a mean and standard deviation of -10 and 12 percent respectively. This particular distribution was chosen because before the Hurricane Debbie experiments meteorologists participating in Project STORMFURY were of the opinion that if the seeding operation were properly performed, a reduction in maximum wind speeds of the order of 10% could be realistically expected. This value was

Table H-2. Results of Hypothesis Testing.

<u>Case 1</u> H_1 = N(-.03, .12), Curve A, Fig. H-2;
H_2 = N(O, .12), Curve C, Fig. H-2.

Experiment (E_n)	Evidence	Probability	
	$(EV(H_1 \mid E_nC)$	H_1	H_2
Assumed before Debbie experiments	0	.5	.5
Debbie 18 Aug. 69 (-30%)*	2.57863	.644	.356
Debbie 20 Aug. 69 (-15%)*	3.80005	.706	.294

<u>Case 2</u> H_1 = N(-.10, .12), Curve B, Fig H-2;
H_2 = N(O, .12), Curve C, Fig. H-2.

Experiment (E_n)	Evidence	Probability	
	$(EV(H_1 \mid E_nC)$	H_1	H_2
Assumed before Debbie experiments	0	.5	.5
Debbie 18 Aug. 69 (-30%)*	7.5398	.850	.150
Debbie 20 Aug. 69 (-15%)*	10.5557	.919	.081

<u>Case 3</u> H_1 = N(-.10, .12) Curve B, Fig. H-2;
H_2 = N(O, .12), Curve C, Fig. H-2.

Experiment (E_n)	Evidence	Probability	
	$(EV(H_1 \mid E_nC)$	H_1	H_2
Assumed before Debbie experiments	-9.5425	.1	.9
Debbie 18 Aug. 69 (-30%)*	-2.0027	.387	.613
Debbie 20 Aug. 69 (-15%)*	1.0132	.558	.442

* Observed maximum wind speed change.

based partly on the results obtained from the Esther and Beulah experiments and on rough calculations of the location and amount of heat that would be released by the seeding experiments and the resulting wind speed changes.

This distribution indicates a probability of 80% that a wind-speed reduction would be observed after each seeding and a 50% chance that the reduction would be more than 10%. The computed results from equation (H-1) indicate that the probability of the truth of hypothesis H_1 compared with H_2 reaches 92% based on the results of the two Debbie experiments.

Many meteorologists have been quite skeptical about the possibility that the eyewall seeding experiment would reduce the maximum wind speeds. If we take this view and say that before Hurricane Debbie experiments we believed that there was only one chance in 10 that the seeding experiment would result in a 10% reduction in the maximum wind speeds, then our results would follow those illustrated for case 3 in table H-2. That is, the hypotheses H_1 and H_2 would be the same as those used for obtaining the results listed in case 2, but instead of assuming that they were equally probable before the experiments, we assume that H_2 is nine times more likely than H_1. As a result of the two Debbie experiments, the accumulated evidence indicates that the probability of the truth of H_1 compared with H_2 has increased from 10% to approximately 56% and that, similarly, the probability of the truth of H_2 compared with H_1 has decreased from 90% to approximately 44%.

UPDATING THE PROBABILITY DISTRIBUTIONS

In the preceding section one approach was used in an attempt to answer the basic question as to whether the seeding operation actually caused the changes observed in the seeded storms. In this section a slightly different approach is used in an attempt to answer that same question.

We would like to determine what we can say about the mean change of maximum wind speeds as a result of our sequence of experiments and, given a similar experiment, what changes can we expect. To accomplish this task, we assume the outcome of seeding events to consist of a continuous set. We can then write Bayes' equation in the following form, using probability densities (Tribus, 1969, p. 79):

$$P(\alpha|E_iX) = \frac{P(\alpha|X)\; P(E_i|\alpha X)}{P(\alpha|X)\; P(E_i|\alpha X)} d\alpha \qquad \text{(H-2)}$$

where

E_i is the percentage of change in the maximum wind speeds measured after the i^{th} seeding experiment,

α is a continuous variable representing the average percentage of change in the maximum wind speeds,

X is all background information,

$P(\alpha|X)$ is the probability distribution prior to the seeding experiment,

$P(E_i|\alpha X)$ is the probability of observing a reduction E_i, given a mean reduction of α, and

$P(\alpha|E_iX)$ is the updated probability destribution obtained from the application of (H-2) and is interpreted as the probability that an average change in maximum wind speeds of size α has occurred, given a seeding experiment result.

We assume the distributions $P(\alpha|X)$ and $P(E_i|\alpha X)$ are normally distributed as was proposed earlier, i.e., we have probability densities of the form

$$P(\alpha|X) = N(\mu_1, \sigma_1) \qquad \text{(H-3)}$$

and

$$P(E_i|\alpha X) = N(\alpha, \sigma_2) \; . \qquad \text{(H-4)}$$

From (H-2), (H-3), and (H-4) we obtain

$$P(\alpha|E_nX) = N(\mu, \sigma) \qquad \text{(H-5)}$$

with

$$\mu = \frac{\mu_1\sigma_2^2 + \sigma_1^2 \sum_{i=1}^{n} E_i}{\sigma_2^2 + n\sigma_1^2}$$

and

$$\sigma = \frac{1}{\sqrt{\frac{1}{\sigma_1^2} + \frac{n}{\sigma_2^2}}}$$

for the sequence of n experimental data symbolized by E_n. We are introducing a family of probability distributions for the maximum wind speed change after seeding of the form H = normal (mean = α, standard deviation σ_2) and use equation (H-2) to obtain equation (H-5) after a sequence of seeding experiments.

The problem then becomes one of selecting appropriate normal distributions to represent $P(\alpha|X)$ and $P(E_i|\alpha X)$. For $P(\alpha|X)$, i.e., the prior distribution, we should use all background information, such as theoretical calculations, results of previous experiments, climatology, etc. Before the Debbie experiments, such information indicated that a wind speed reduction should occur, i.e., Esther and Beulah experimental results and theoretical calculations. However, to avoid any bias in favor of the seeding reduction, we chose the distribution $P(\alpha|X) = N(0, .12)$. In a sense, we are saying that we expect the seeding to have no effect and that the natural fluctuations will continue to play their role. For σ_2 (eq. (H-4)), we chose .12, the same as climatology. Equation (H-5) was then used to obtain the updated probability distribution for the average change in maximum wind speeds. The prior distribution and the updated distribution are shown in figure H-3.

We then ask: What is the probability that a given change in maximum wind speeds will occur given a similar seeding experiment? To answer this question, we let

W = a maximum wind speed change (%)

and

E = a similar seeding experiment.

Then we take

$$P(W|EX) = \int_\alpha P(W|E\alpha X)\; P(\alpha|EX)d\alpha \qquad \text{(H-6)}$$

with

$$P(W|E\alpha X) = P(W|\alpha X) = N(\alpha, \sigma_2 = .12),$$

and

$P(\alpha|E_n X)$ = probability previously computed.

We then obtain

$$P(W|EX) = N(\mu', \sigma') \tag{H-7}$$

with

$$\mu' = \mu \text{ and } \sigma' = \sqrt{\sigma^2 + \sigma_2^2} ,$$

where

$P(W|EX)$ = the probability that a maximum wind speed reduction of size W will be observed, given a similar seeding experiment.

The results of these calculations are shown in figure H-3.

In the next set of calculations (fig. H-4), all the factors remained the same as above except that the prior probability ($P(\alpha|X)$) was changed to reflect a very uncertain view of the probable outcome of a seeding operation. The standard deviation was chosen to be .3, which results in a very "flat" distribution.

The accumulative probabilities were computed for the dis-distribution $P(W|EX)$ shown in figures H-3 and 4. The results, shown in figure H-5, indicate for both cases a .5 probability that a reduction in maximum wind speed of 15% or more can be expected with a similar experiment. For the first ($P(W|EX)=N(-0.15, 0.139)$) and second ($P(W|EX)=N(-0.15, 0.211)$) cases, a wind speed reduction should occur with a probability of .85 and .75 respectively for a seeding experiment similar to those conducted in Hurricane Debbie 1969.

SUMMARY AND CONCLUSIONS

In the preceding sections, we have presented numerous computations on the probability that hurricane seeding experiments caused or will cause the changes observed in the maximum wind speeds in a seeded storm.

In the first part of the paper, two basic hypotheses were examined to determine whether the results observed after a seeding experiment came from a population represented by the climatological distribution or from some distribution generated by the seeding experiment tested. A range of continuous

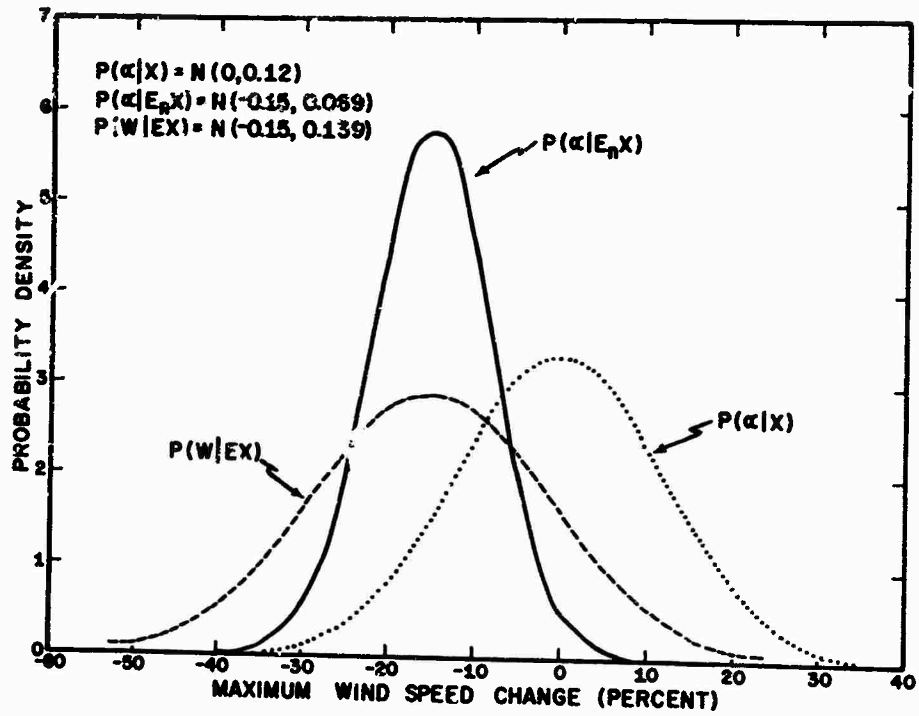

Figure H-3. The updated probability distribution ($P(\alpha|E_nX)$) obtained based on Bayes' eq.(H-2), the Hurricane Debbie seeding results, and the probability distribution assumed before application of the experimental results ($P(\alpha|X)$) and the probability that a given wind speed reduction W will occur, given a similar seeding experiment ($P(W|EX)$).

distributions was chosen for the seeding hypothesis for comparison with the climatological distribution. Two of these distributions were presented in this paper. Both were normal distributions with means of -.03 and -.1 respectively and standard deviations of .12. Based on the results obtained from the Hurricane Debbie experiments, we verified that these two distributions fit the data better than the climatological distribution and that the distribution with a mean of -.1 was better than one with a mean of -.03. Using the results of the two Debbie experiments, we found that the probability that the distribution with a mean of -.1 was correct compared with climatology and reached .92 while that for the distribution of -.03 reached .71. These probabilities were obtained without any evidence assumed in favor of the climatological or chosen distribution prior to the Debbie experiments.

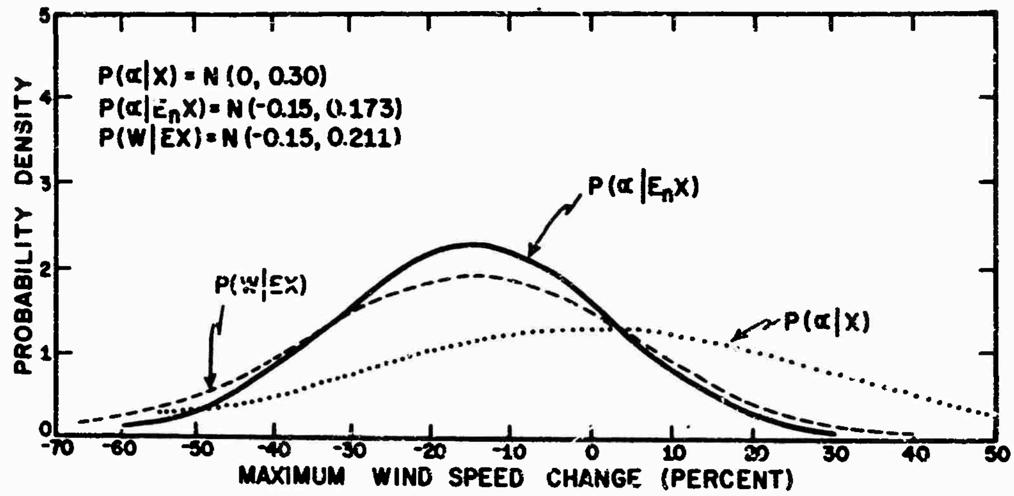

Figure H-4. *Same as fig. H-3, except that the standard deviation of the prior probability distribution (P(α|X)) is chosen to be .3 compared with .12 used in the construction of fig. H-3.*

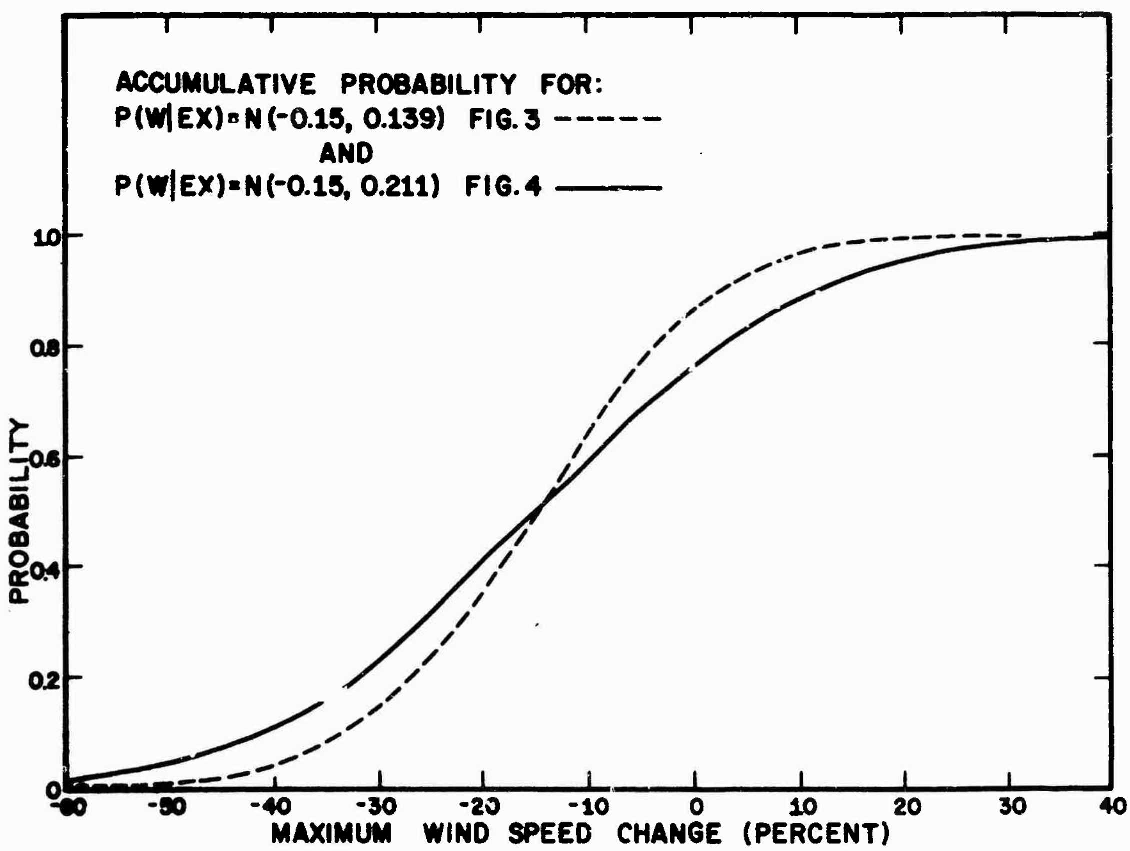

Figure H-5. *The accumulative probability for the distributions P(W|EX) illustrated in figs. H-3 and 4.*

Other distributions of the same form could have been chosen that would fit the data even better. Therefore, in the second portion of the paper we introduced a family of probability distributions of the same form for the average maximum wind speed change after seeding. The resulting computations produced an updated probability distribution based on the seeding results obtained in Hurricane Debbie 1969. Computations were then made to determine the probability that a given wind speed reduction would be observed given a similar seeding experiment. These results are summarized in figure H-5.

The results of all these computations indicate that the experimental evidence gained from the Hurricane Debbie seeding experiments strongly suggests an effect due to the seeding. The Beulah, Esther, and model experiments seem to indicate a similar effect.

If we accept the validity of the application of Bayes' equation in the two forms applied to this particular problem, then regardless of how pessimistic we may have been before the Hurricane Debbie seeding experiments, we must certainly now reevaluate our opinions.* This fact is particularly illustrated by case 3 listed in table H-2 and figures H-4 and 5. In both cases, quite pessimistic views toward the probable success of the seeding experiment were taken as prior probabilities, and yet the results indicate a strong probability that the seeding of a hurricane in a manner similar to that used in the Hurricane Debbie experiments should reduce the maximum wind speeds.

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*These conclusions are similar to those reached by Dr. E. Epstein of the University of Michigan based on a slightly different approach (personal communication).

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